GLOBAL QCD ANALYSES & PARTON DENSITIES

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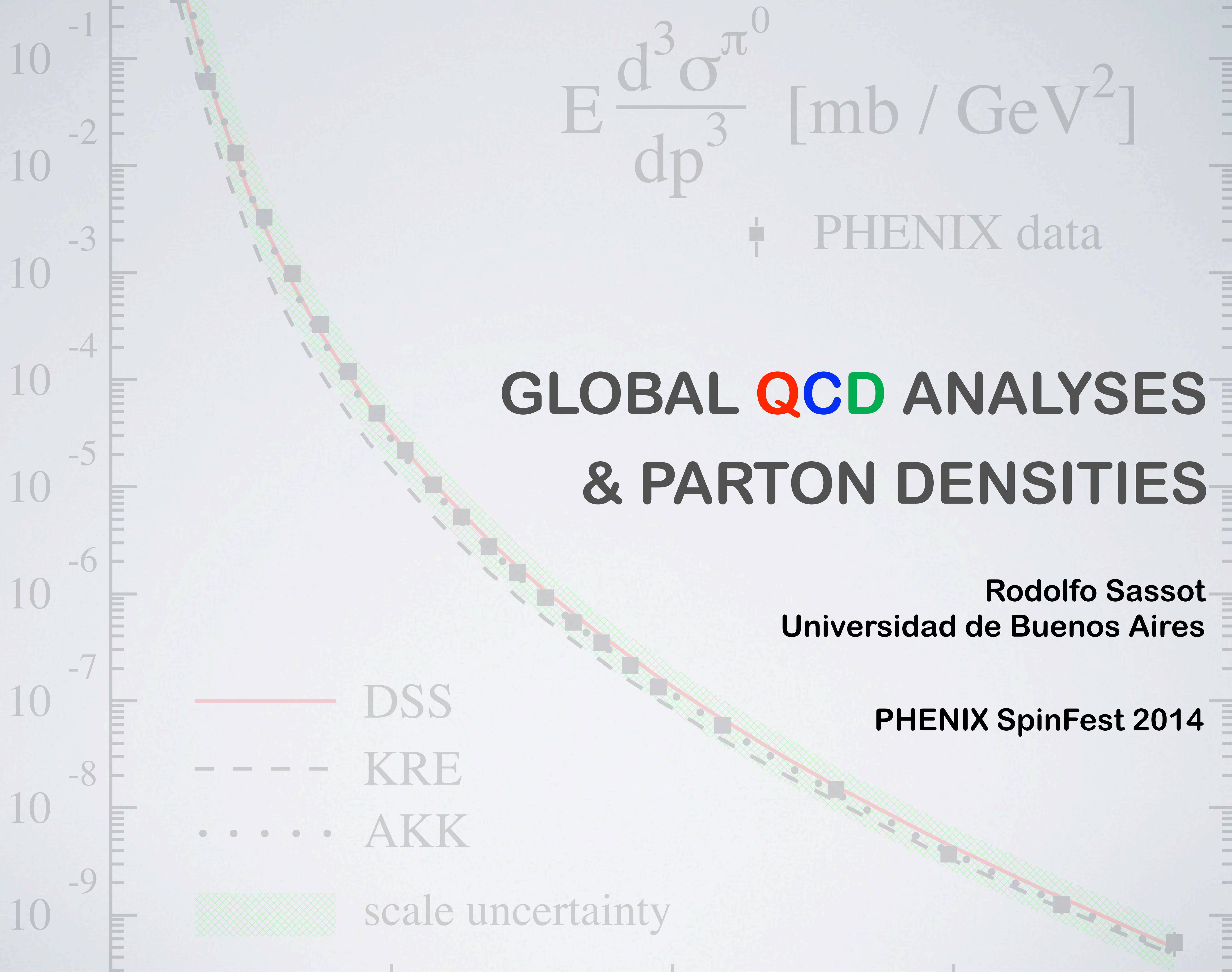
PHENIX SpinFest 2014



Third Lecture: Polarized (helicity) PDFs

3.0 Helicity PDFs framework

First NLO DIS analysis 1996

3.1 Why DIS is not enough? *'90s, GRSV, AAC, BB, NNPDFs*

First NLO DIS+SIDIS analysis 1998

3.2 Why SIDIS is not enough? *DSS, DS, DNS, LSS*

First NLO DIS+SIDIS+pp analysis 2008

3.3 Can $pp \to \pi^0/jets$ help? *DSSV*

3.4 Compass SIDIS update *DSSV+*

3.5 RHIC preliminary/projections *DSSV++*

3.6 EIC projections

3.7 DSSV gluon update (2014)

3.8 NNPDFs reweighting (2014)

3.9 Outlook

3.0 Helicity PDFs

factorization

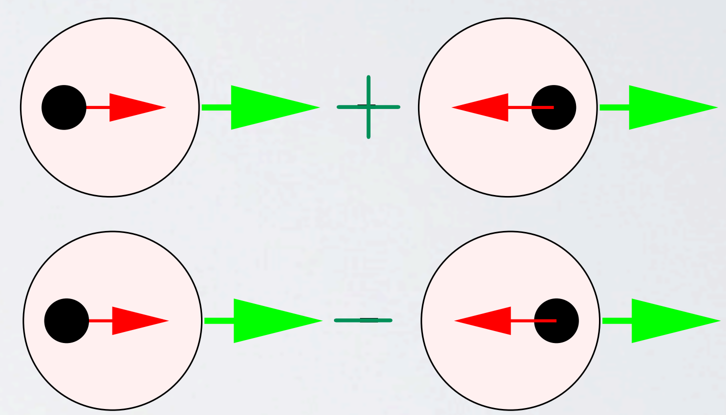
universality

scale dependence

$$f_i(x,Q^2) \to \begin{cases} f_i^+(x,Q^2) & \text{same helicity as target} \\ f_i^-(x,Q^2) & \text{opposite helicity} \end{cases}$$

$$f_i(x,Q^2) \equiv f_i^+(x,Q^2) + f_i^-(x,Q^2)$$

$$\Delta f_i(x,Q^2) \equiv f_i^+(x,Q^2) - f_i^-(x,Q^2)$$



$$\Delta\sigma(ep \to eX) \equiv \sigma(\vec{e}p^+ \to eX) - \sigma(\vec{e}p^- \to eX)$$

$$= \Delta\hat{\sigma}_i \otimes \Delta f_i$$

$$F_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2[q(x,Q^2) + \bar{q}(x,Q^2)] \longrightarrow g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)]$$

3.1 Why DIS is not enough?

inclusive DIS gives

$$g_1^p(x,Q^2)\, g_1^n(x,Q^2)$$

unknowns

$$\Delta u\, \Delta\overline{u}\, \Delta d\, \Delta\overline{d}\, \Delta s\, \Delta\overline{s}\, \Delta g$$

assuming $\Delta u^p = \Delta d^n$ etc.

evolution *in principle* could help:

$$\begin{aligned}
\Delta q_3^{NS} &\equiv (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d}) \\
\Delta q_8^{NS} &\equiv (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2\,(\Delta s + \Delta\bar{s}) \\
\Delta\Sigma &\equiv (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s}) \\
\Delta g &
\end{aligned}$$

$$\frac{d}{d\ln Q^2}\Delta q^{NS} = \frac{\alpha_s}{2\pi}\Delta P_{qq}^1 \otimes \Delta q^{NS}$$

$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix}\Delta P_{qq}^1 & 2f P_{qg}^1 \\ \Delta P_{gq}^1 & P_{gg}^1\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix}$$

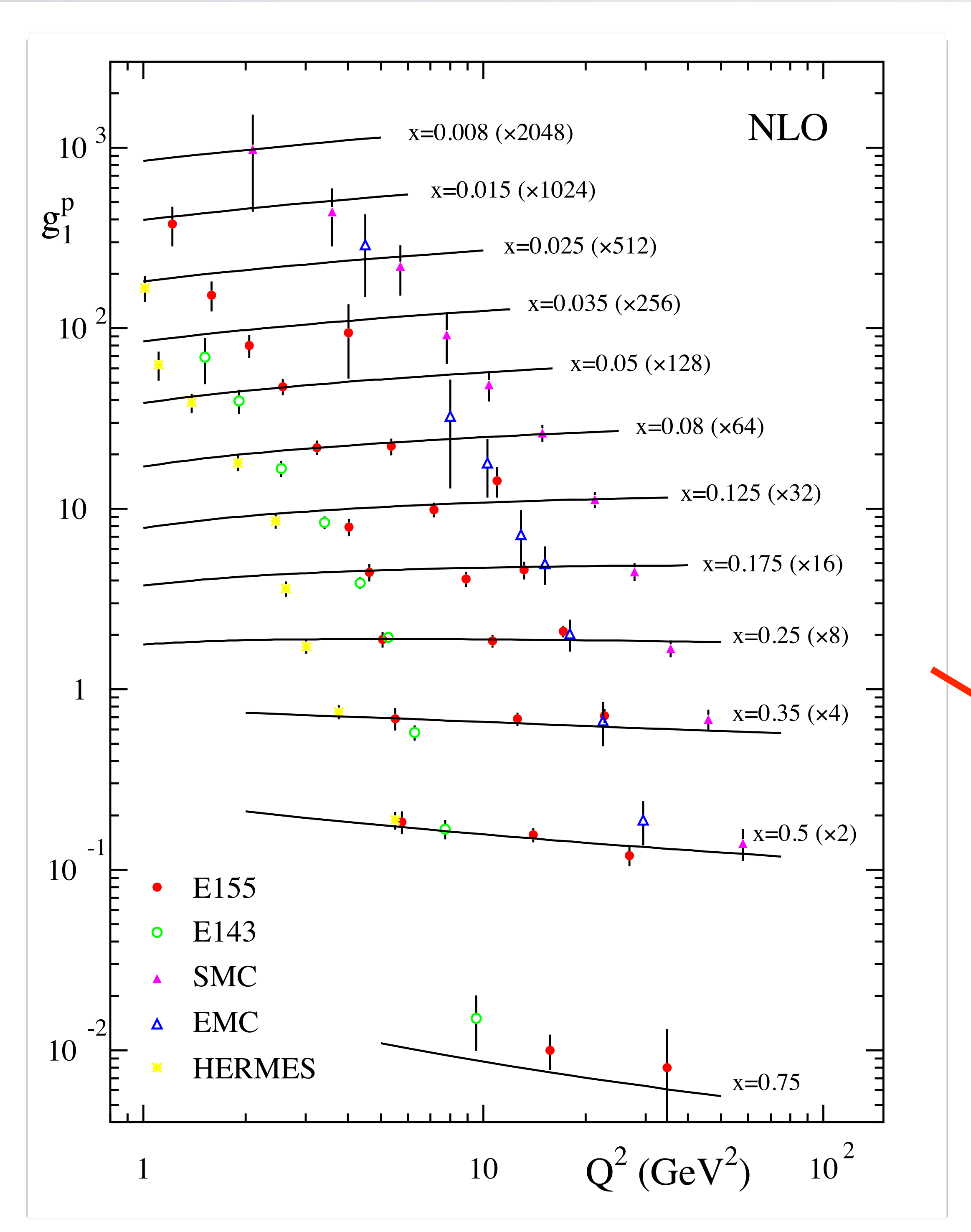
$$\begin{aligned}
g_1^N(x,Q^2) &= \left(\pm\frac{1}{12}\Delta q_3^{NS} + \frac{1}{36}\Delta q_8^{NS} + \frac{1}{9}\Delta\Sigma\right) \otimes \left(1 + \frac{\alpha_s}{2\pi}\Delta C_q\right) \\
&+ \sum_q e_q^2 \frac{\alpha_s}{2\pi}\Delta g \otimes \Delta C_g .
\end{aligned}$$

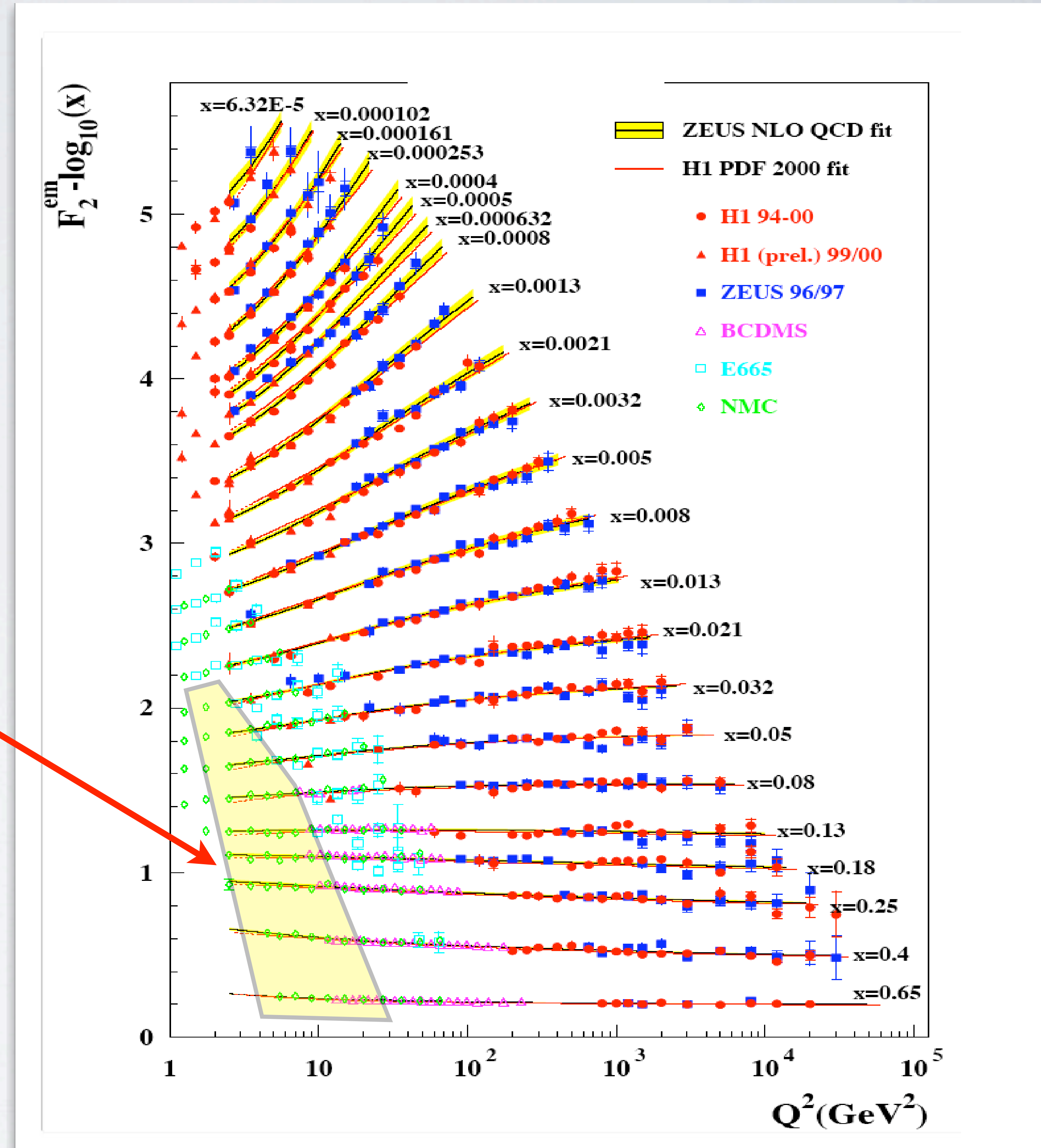
$$\Delta q_3^{NS}, \Delta q_8^{NS}, \Delta\Sigma, \Delta g \longrightarrow (\Delta u + \Delta\overline{u}), (\Delta d + \Delta\overline{d}), (\Delta s + \Delta\overline{s}), \Delta g$$

wrong! $\cancel{\xrightarrow{SU(3)}}$ $\Delta u_v, \Delta d_v, \Delta\bar{q}, \Delta g$

3.1 Why DIS is not enough?

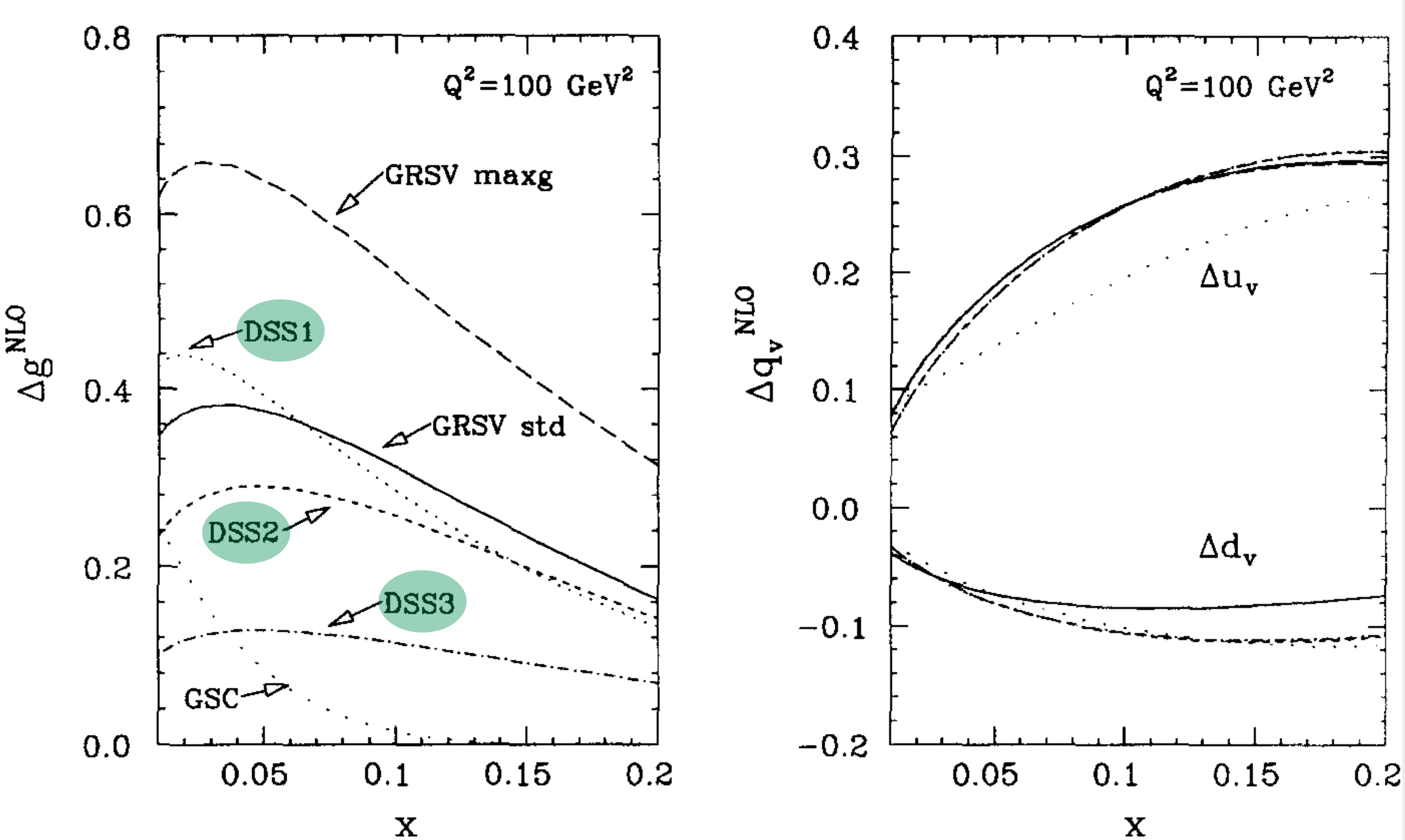
evolution *in practice* is of little help:

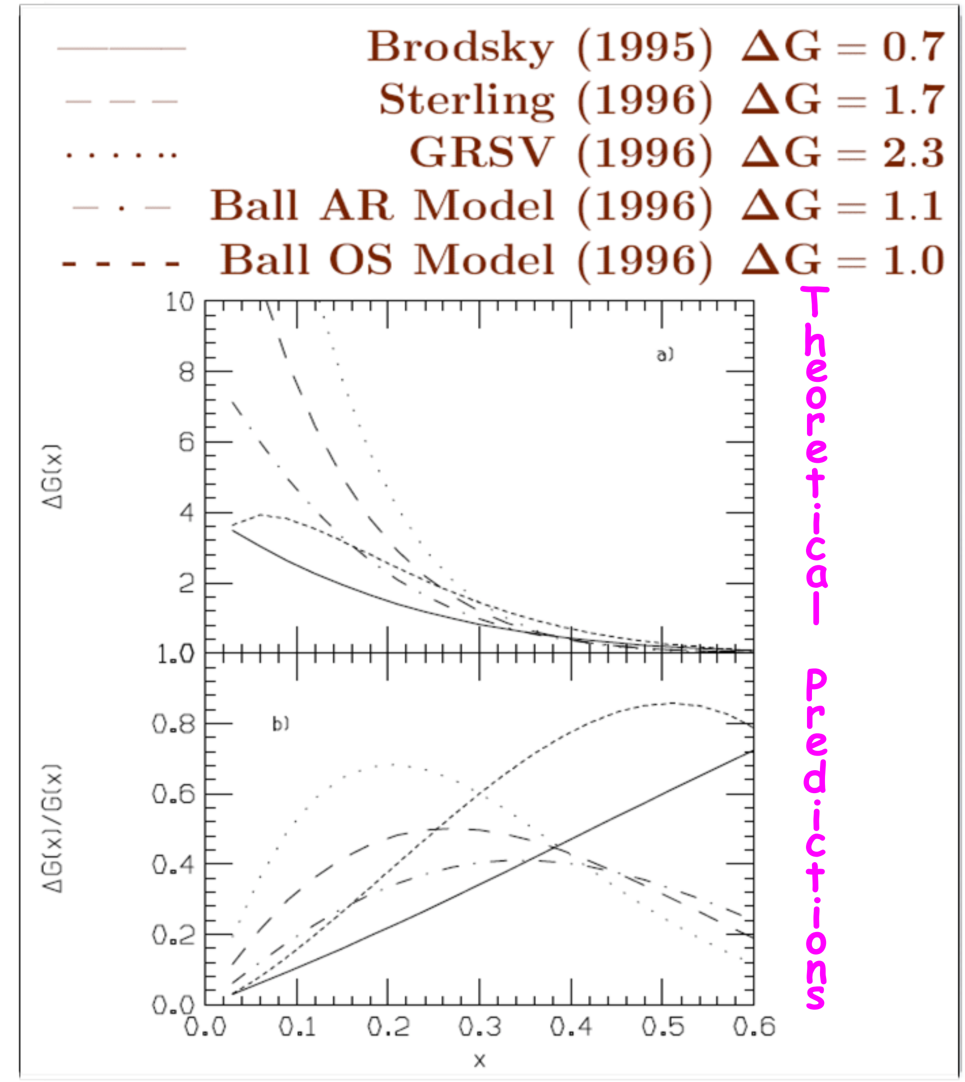




reduced kinematical coverage and precision compared to unpolarized case

3.1 Why DIS is not enough?





Not a surprise that different fits provide very different pdfs

Similarly for first moment of gluon polarized pdf

same group, same data: three different gluons!

mea culpa

3.2 Why SIDIS is not enough?

helps with sea quarks: *analyzing power of final state hadrons*

$$D_1 = D_u^{\pi^+} = D_{\bar d}^{\pi^+}$$
$$D_2 = D_d^{\pi^+} = D_{\bar u}^{\pi^+}$$
$$D_3 = D_s^{\pi^+} = D_{\bar s}^{\pi^+}$$

$$2g_{1p}^{\pi^{+(-)}} \simeq \frac{4}{9}\Delta u \otimes D_{1(2)} + \frac{1}{9}\Delta d \otimes D_{2(1)} + \frac{4}{9}\Delta \bar u \otimes D_{2(1)} + \frac{1}{9}\Delta \bar d \otimes D_{1(2)} + \frac{2}{9}\Delta s \otimes D_3 + \frac{2}{9}\Delta \bar s \otimes D_3$$

but for a price: FFs dependence

so far consistent -no visible tensions?-

needs independent check (W)

kaons??

very little help with gluons:

more precise ΔΣ, better Δg

same kinematics as DIS

$O(\alpha_s)$ relative suppression

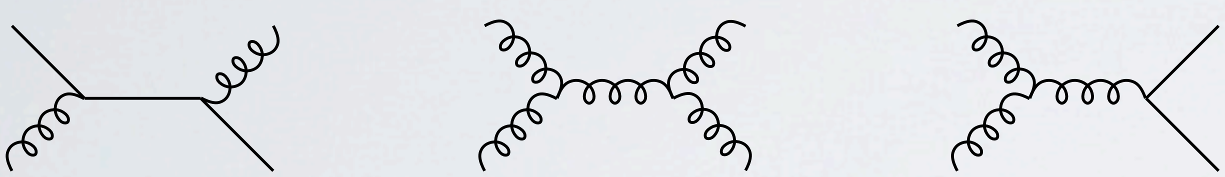
charm and high pT hadrons

huge exp. & Th errors

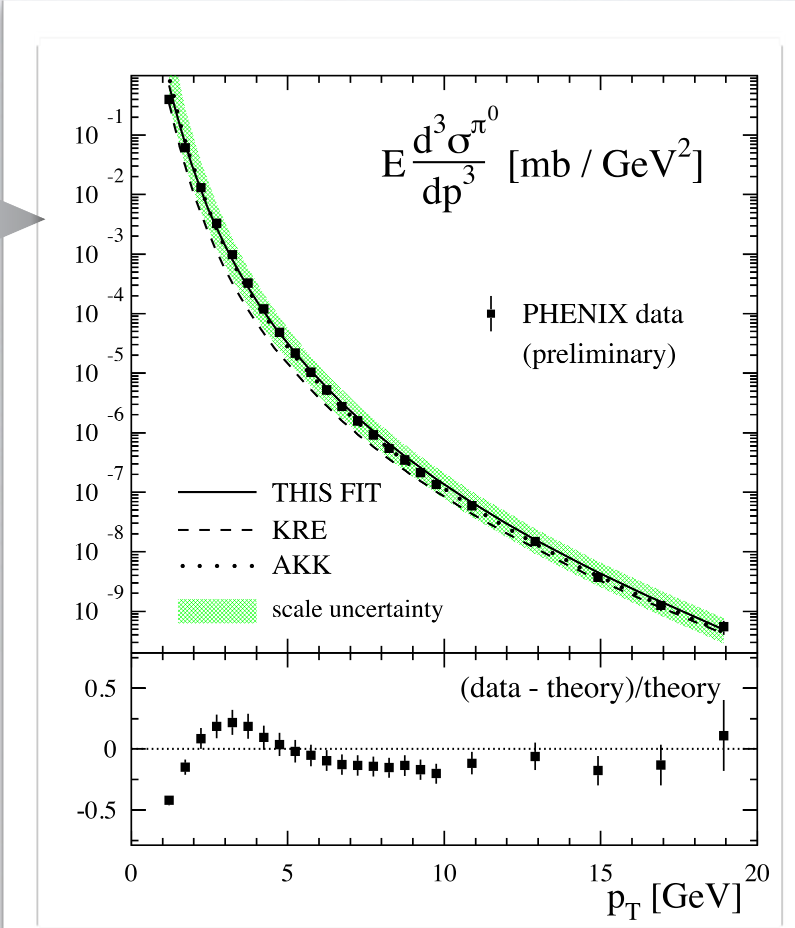
3.3 Can $pp \to \pi^0$/*jets* help?

To measure gluon → find observable where gluon starts at LO and dominates cross section

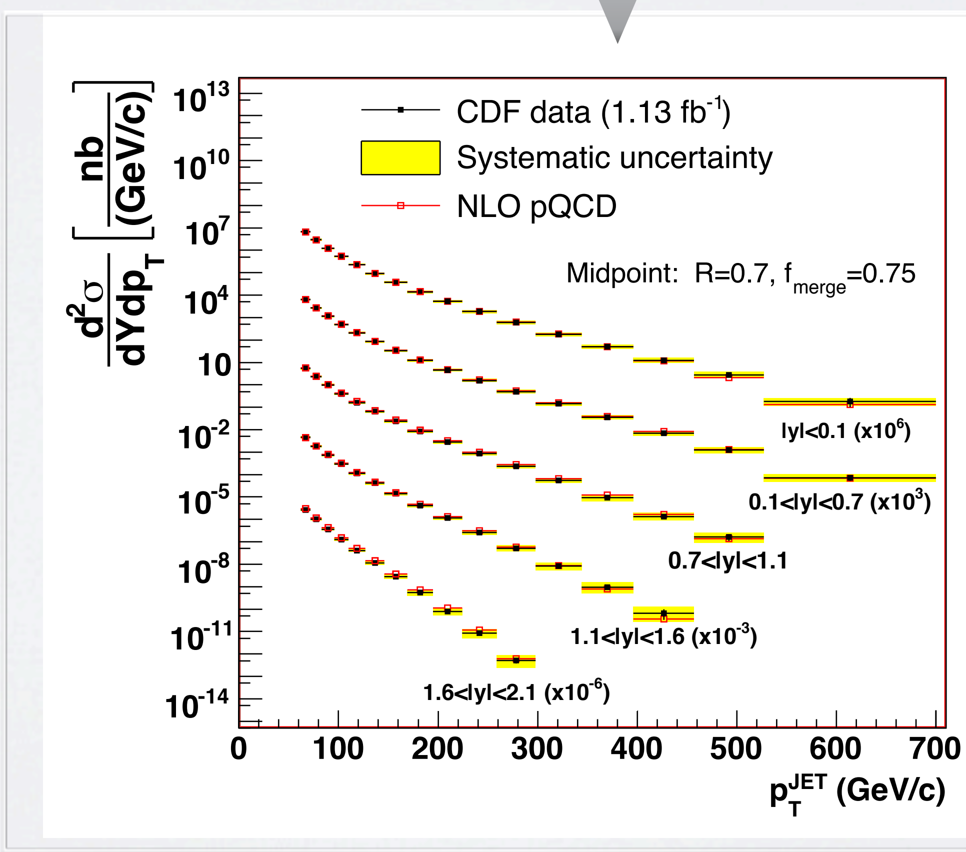
pp collisions: several processes initiated by gluons



$pp \to \pi^0 X$



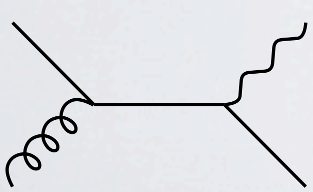
$pp \to jets\ X$



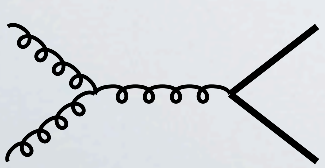
known NLO corrections ✔

work in unpolarized case ✔

other interesting candidates:



$pp \to \gamma X$



$pp \to cc\ X$

3.3 Can $pp \to \pi^0$/*jets* help?

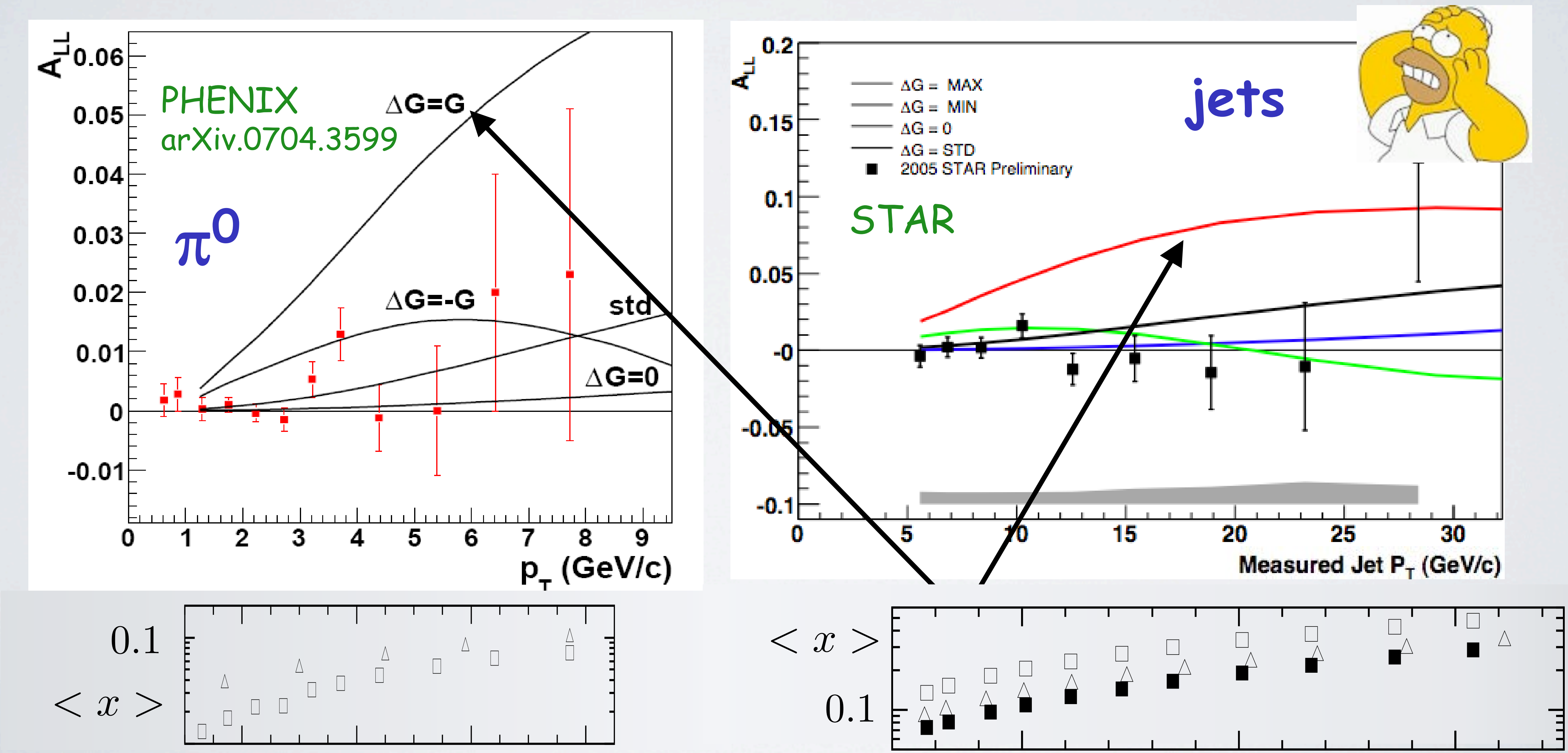
they have already done: *ruled out large gluon polarization scenarios* ✔

however[1]: *so small polarization that errors prevent other direct comparisons* ✘

however[2]: *kinematic entanglement*

each p_T bin probes a different x
p_T is the factorization scale

different pieces of Δg at different Q^2



3.3 Can $pp \rightarrow \pi^0/jets$ help?

Double spin asymmetries

$$A_{LL} \equiv \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} \equiv \frac{d\Delta\sigma}{d\sigma}$$

π^0 *jets* $W^{\pm}$ γ ...

$$d\Delta\sigma \equiv \sum_{ab} \int dx_a \int dx_b \, \Delta f_a(x_a, Q^2) \Delta f_b(x_b, Q^2) \times d\Delta\hat{\sigma}_{ab}(x_a, x_b, p_T, \alpha_s(Q^2), p_T/Q)$$

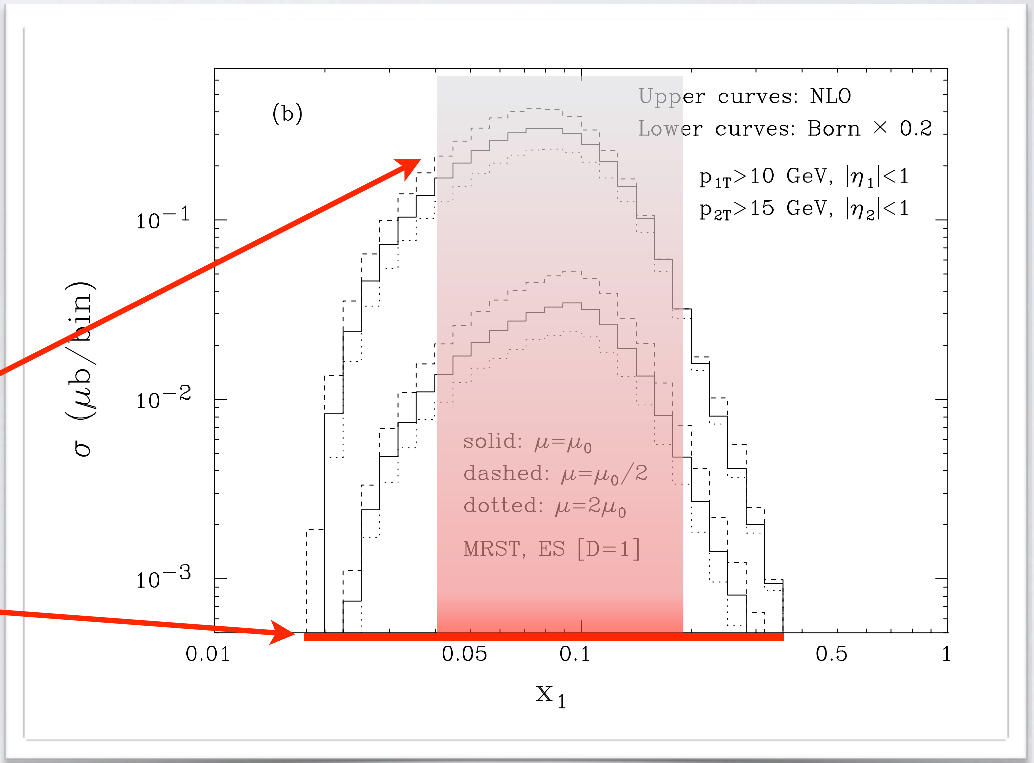
unknowns

$$x_a = (p_{aT} e^{\eta_a} + p_{bT} e^{\eta_b})/\sqrt{s}$$

$$x \sim 2p_T/\sqrt{S}$$

dominated by x~0.04-0.2

a range of x values



Single spin asymmetries : only for Parity violating interactions

$$A_L = -\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \qquad x_{a,b} = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$$

what can we do?

DIS: *no flavor separation, no gluons*

SIDIS: *no gluons, FF-dependence*

pp: *entanglement, limited range*

global analysis

DSSV 2008

D.de Florian, R.S., M. Stratmann, W. Vogelsang

inclusive DIS data $\Delta q + \Delta \bar{q}$ — *50%*

SIDIS data ~ flavor separation — *40%*

RHIC data — *10%*

experiment	data type	data points fitted	χ^2
EMC, SMC	DIS	34	25.7
COMPASS	DIS	15	8.1
E142, E143, E154, E155	DIS	123	109.9
HERMES	DIS	39	33.6
HALL-A	DIS	3	0.2
CLAS	DIS	20	8.5
SMC	SIDIS, $h^{\pm}$	48	50.7
HERMES	SIDIS, $h^{\pm}$	54	38.8
	SIDIS, $\pi^{\pm}$	36	43.4
	SIDIS, $K^{\pm}$	27	15.4
COMPASS	SIDIS, $h^{\pm}$	24	18.2
PHENIX (in part prel.)	200 GeV pp, π^0	20	21.3
PHENIX (prel.)	62 GeV pp, π^0	5	3.1
STAR (in part prel.)	200 GeV pp, jet	19	15.7
TOTAL:		467	392.6

DSSV parameterization

Start evolution at $Q_0^2 = 1\,\mathrm{GeV}^2$

MRST like input (easy to impose positivity)

For (better determined) $u_T = u + \bar{u}\ ,\ d_T = d + \bar{d}$

unpolarized

$$x\Delta f_j(x, Q_0^2) = N_j x^{\alpha_j} (1-x)^{\beta_j} (1 + \gamma_j \sqrt{x} + \eta_j x)$$

For sea and gluons $\bar{u}\,,\, \bar{d}\,,\, \bar{s}\,,\, g$

$$x\Delta f_j(x, Q_0^2) = N_j x^{\alpha_j} (1-x)^{\beta_j} (1 + \eta_j x)$$

node allowed

26-5=21
free
parameters

Small x behavior of sea

$$\alpha_{\bar{u}} = \alpha_{u_T} \qquad \alpha_{\bar{d}} = \alpha_{\bar{s}} = \alpha_{d_T}$$

Normalization related to first moment

$$\Delta U_T - \Delta D_T = (F + D)[1 + \varepsilon_{\mathrm{SU(2)}}]$$

$$\Delta U_T + \Delta D_T - 2\Delta S_T = (3F - D)[1 + \varepsilon_{\mathrm{SU(3)}}]$$

Allow deviations from standard assumptions

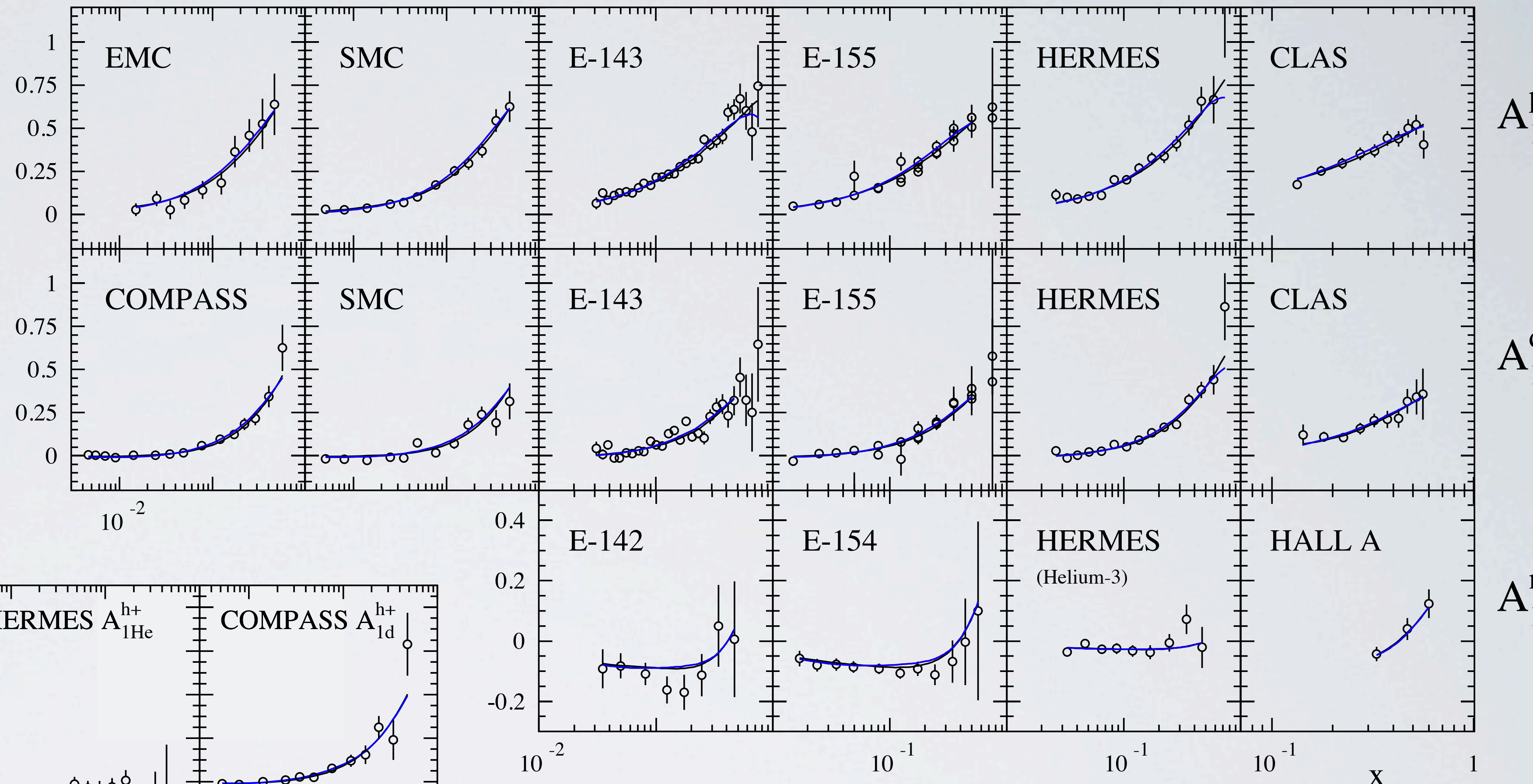
$F + D = 1.269 \pm 0.003\ \ ,\ 3F - D = 0.586 \pm 0.031$

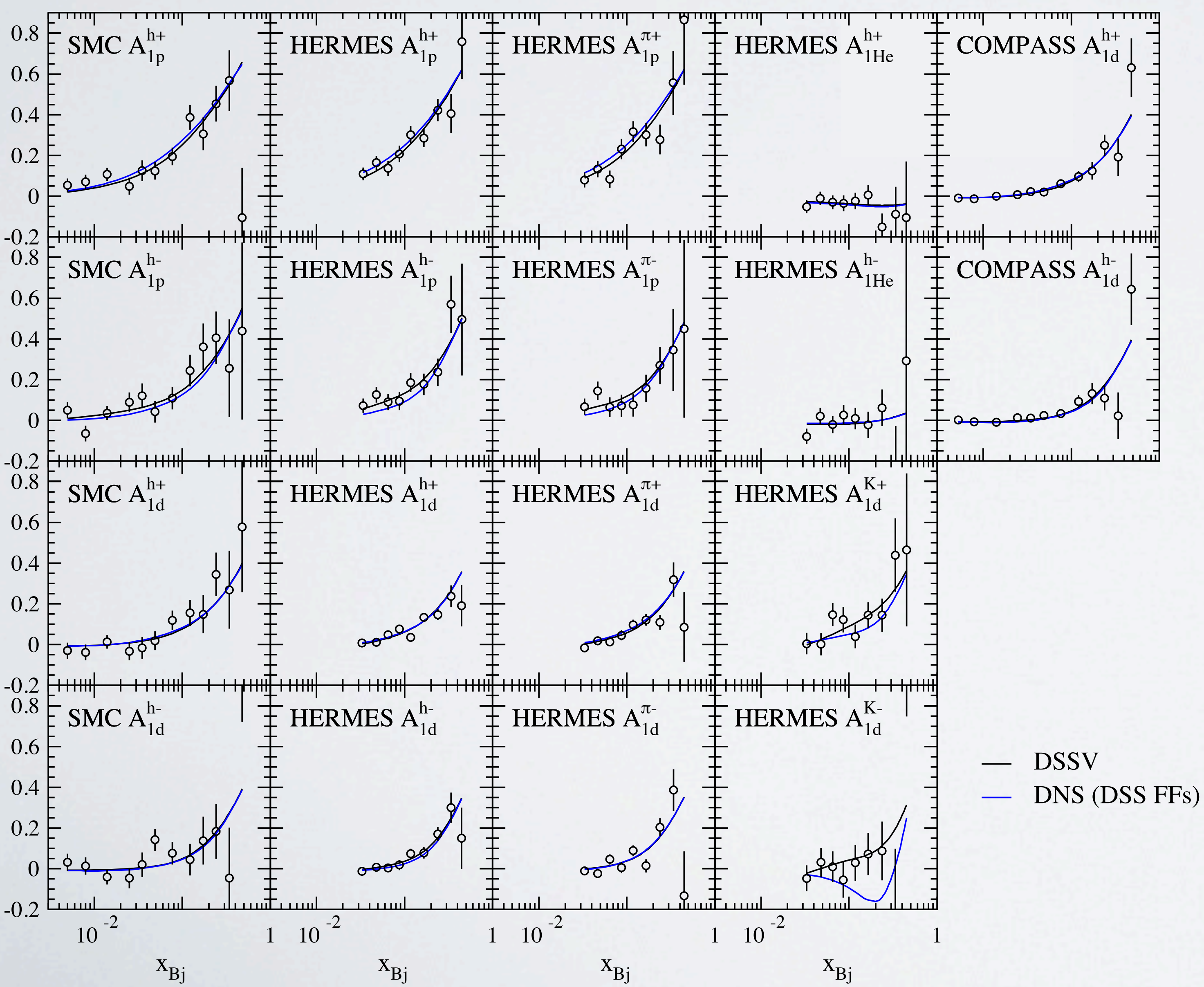
DSSV fit to data

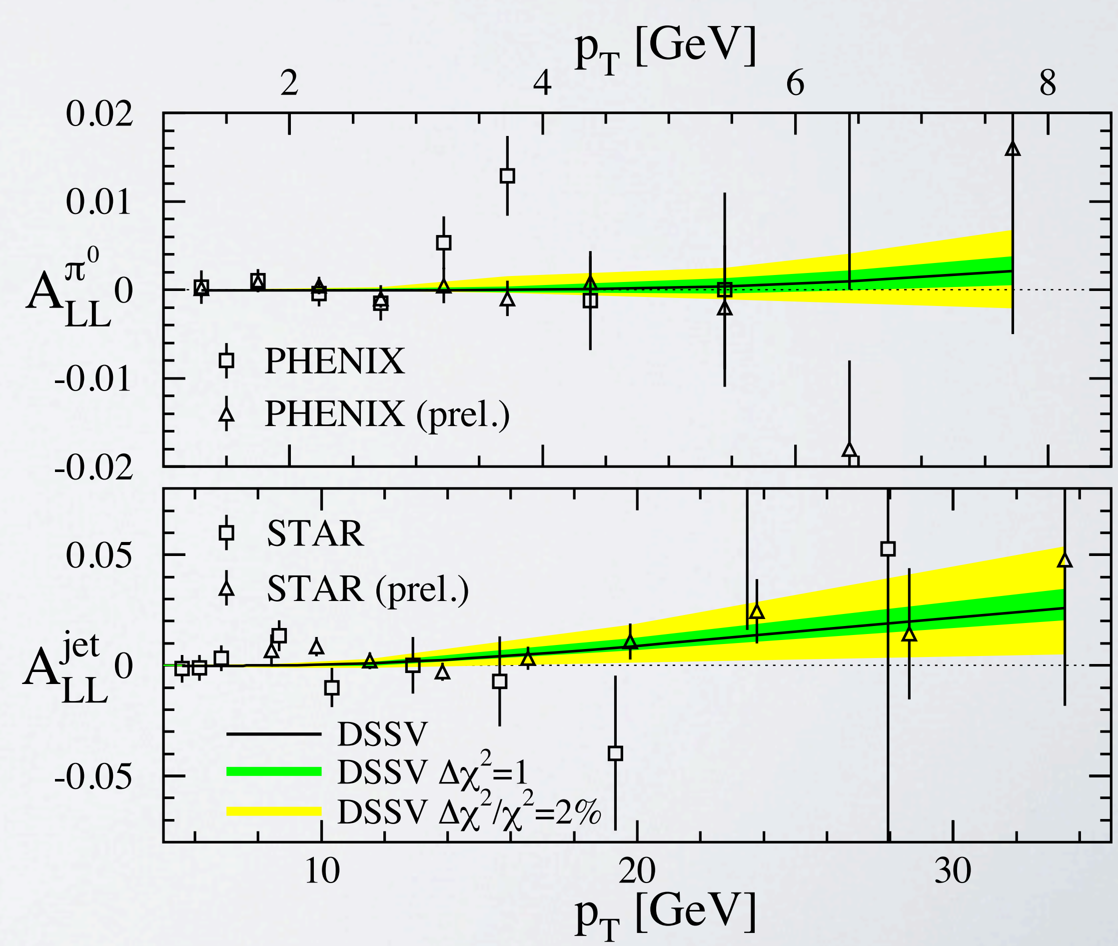
no significant tension

$\chi^2/d.o.f = 0.88$

overestimate syst. inc.







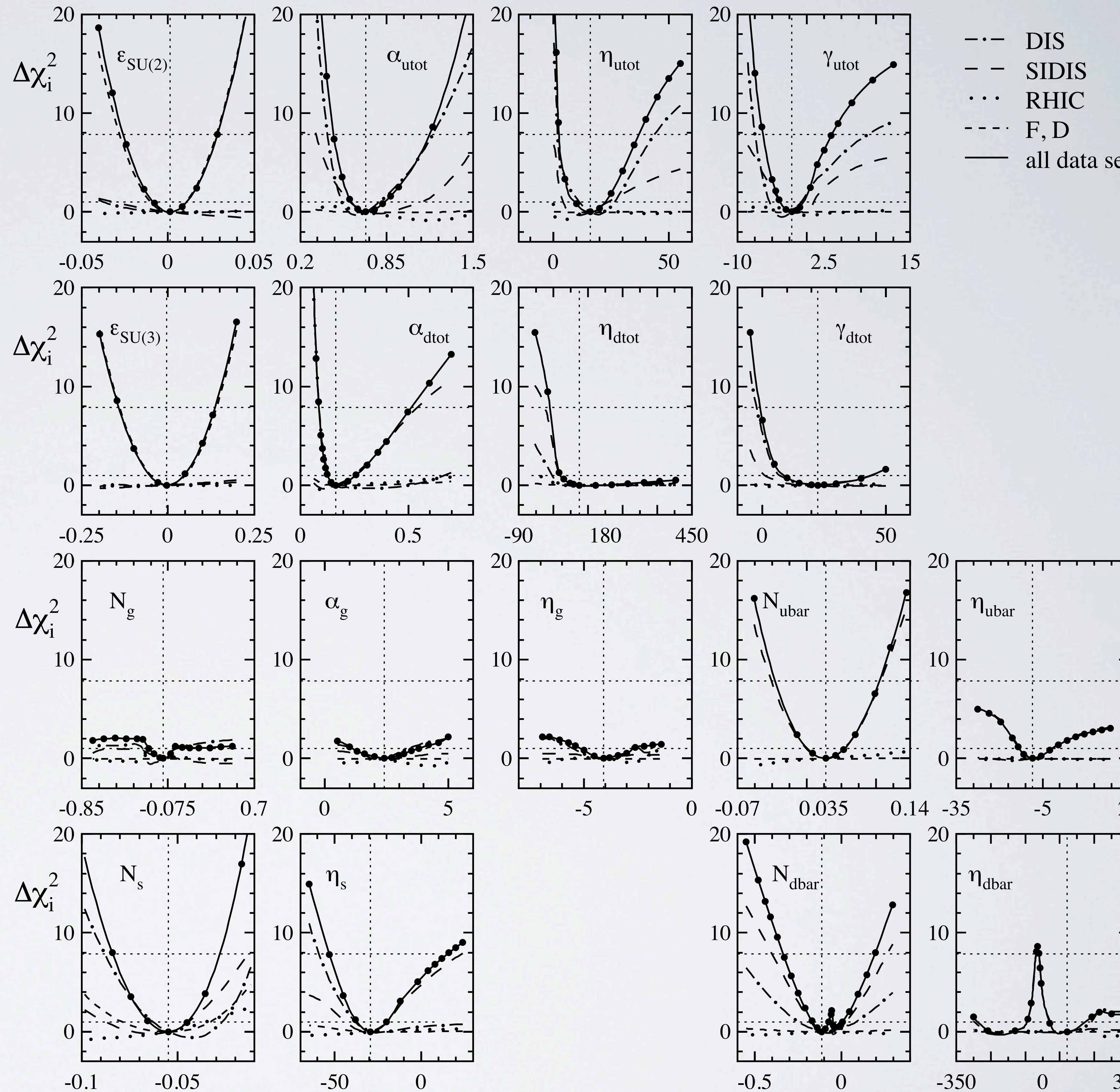
DSSV errors

explore parameters profiles with LM

quadratic?

strong correlations between Δg parameters

non gaussian constraints:
- evolution
- positivity

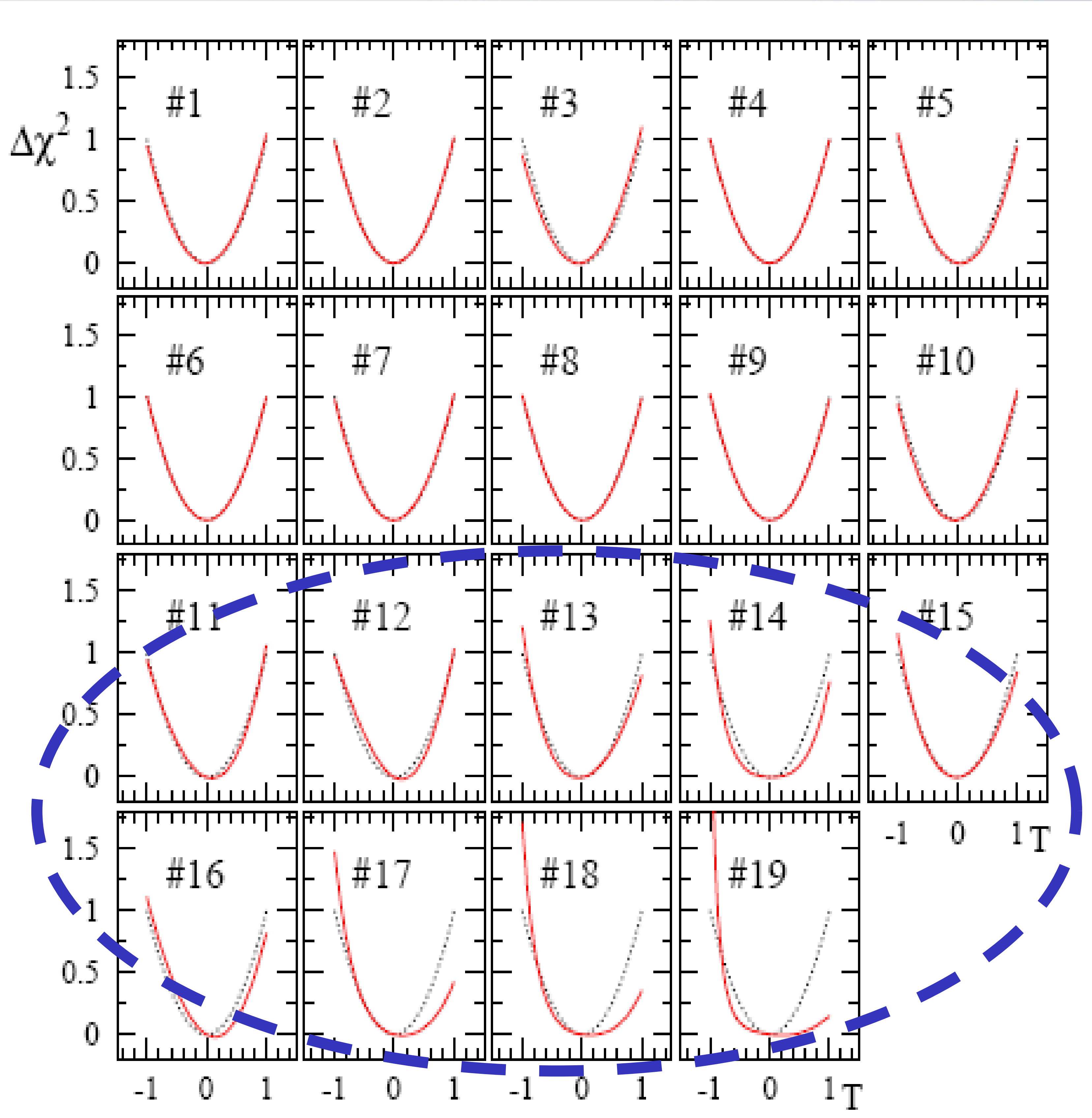


standard Hessian out of question

DSSV errors

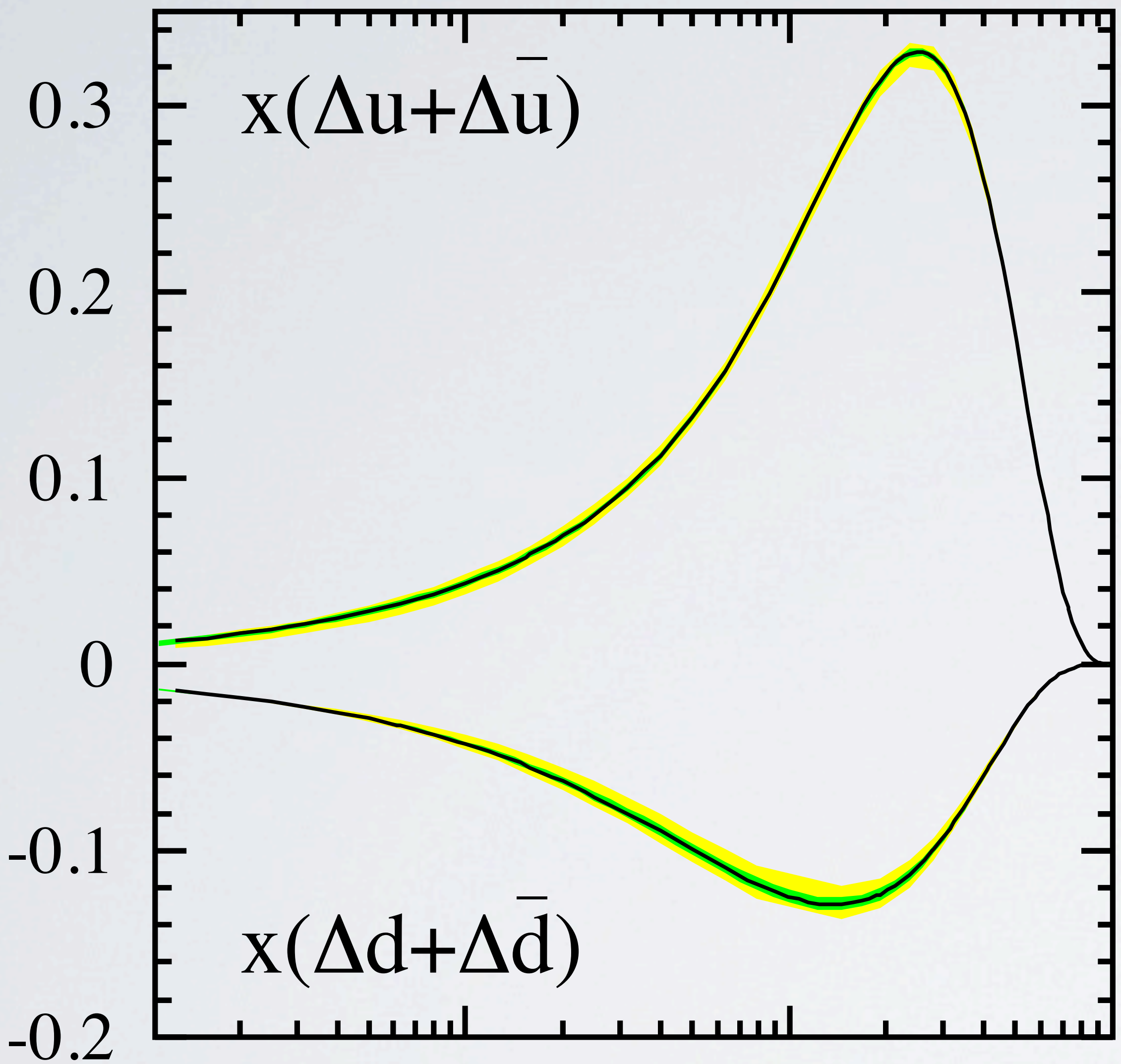
Improved Hessian also fails for $\Delta\chi^2 > 1$

$\Delta\chi^2 = 1$ is insufficient



for a somewhat simplified DSSV fit with 19 parameters

DSSV PDFs



quark + antiquark
pretty well determined : DIS

Green bands corresponds to $\Delta\chi^2 = 1$

Yellow bands corresponds to $\Delta\chi^2/\chi^2 = 2\%$

"Observable" for LM method : truncated moment [0.001 - 1]

~data available

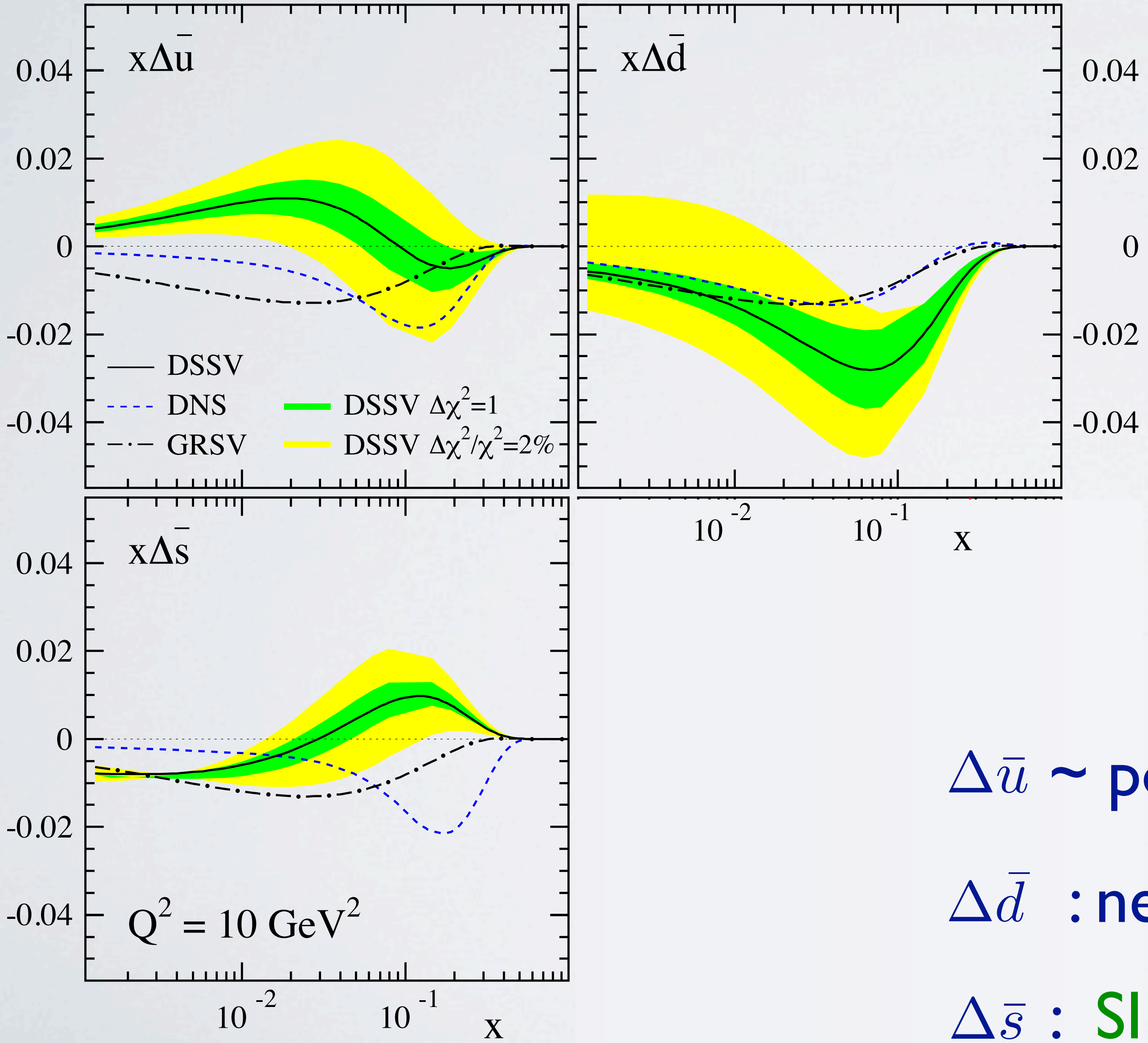
$$\Delta f_j^{1,[x_{\min}-x_{\max}]}(Q^2) \equiv \int_{x_{\min}}^{x_{\max}} \Delta f_j(x,Q^2)dx$$

DSSV sea quarks

"Observable" for LM method : truncated moment [0.001 - 1]

$$\Delta f_j^{1,[x_{\min}-x_{\max}]}(Q^2) \equiv \int_{x_{\min}}^{x_{\max}} \Delta f_j(x,Q^2)dx$$

~data available



	$x_{\min}=0$	$x_{\min}=0.001$	
	best fit	$\Delta\chi^2=1$	$\Delta\chi^2/\chi^2=2\%$
$\Delta u+\Delta\bar{u}$	0.813	0.793 $^{+0.011}_{-0.012}$	0.793 $^{+0.028}_{-0.034}$
$\Delta d+\Delta\bar{d}$	-0.458	-0.416 $^{+0.011}_{-0.009}$	-0.416 $^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	0.028 $^{+0.021}_{-0.020}$	0.028 $^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	-0.089 $^{+0.029}_{-0.029}$	-0.089 $^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	-0.006 $^{+0.010}_{-0.012}$	-0.006 $^{+0.028}_{-0.031}$
$\Delta\Sigma$	0.242	0.366 $^{+0.015}_{-0.018}$	0.366 $^{+0.042}_{-0.062}$

differences with previous fit (DNS): new DSS fragmentation functions

$\Delta\bar{u}$ ~ positive

Robust pattern : ~~SU~~(3) sea

$\Delta\bar{d}$: negative

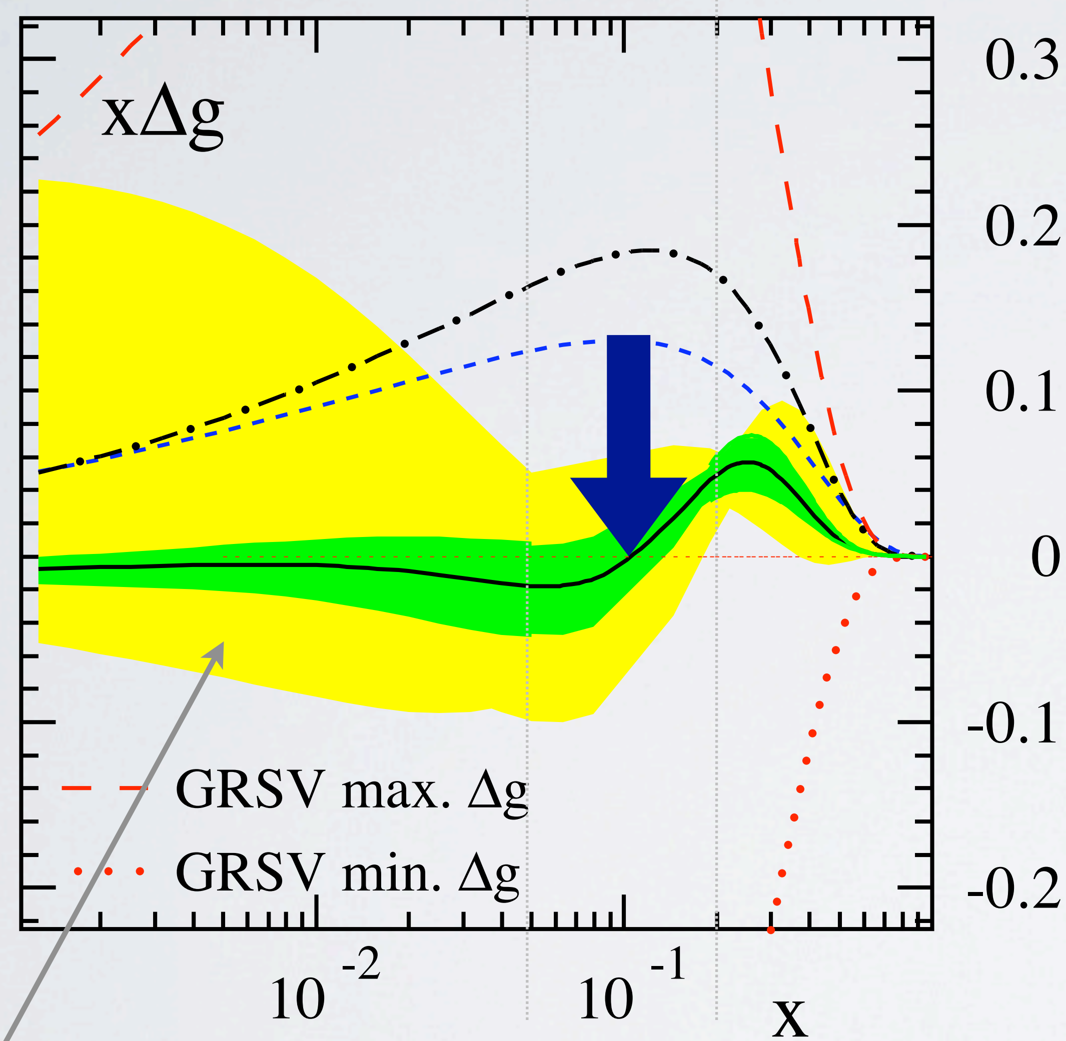
$\Delta\bar{s}$: SIDIS requires positive (HERMES)
but first moment negative (DIS)

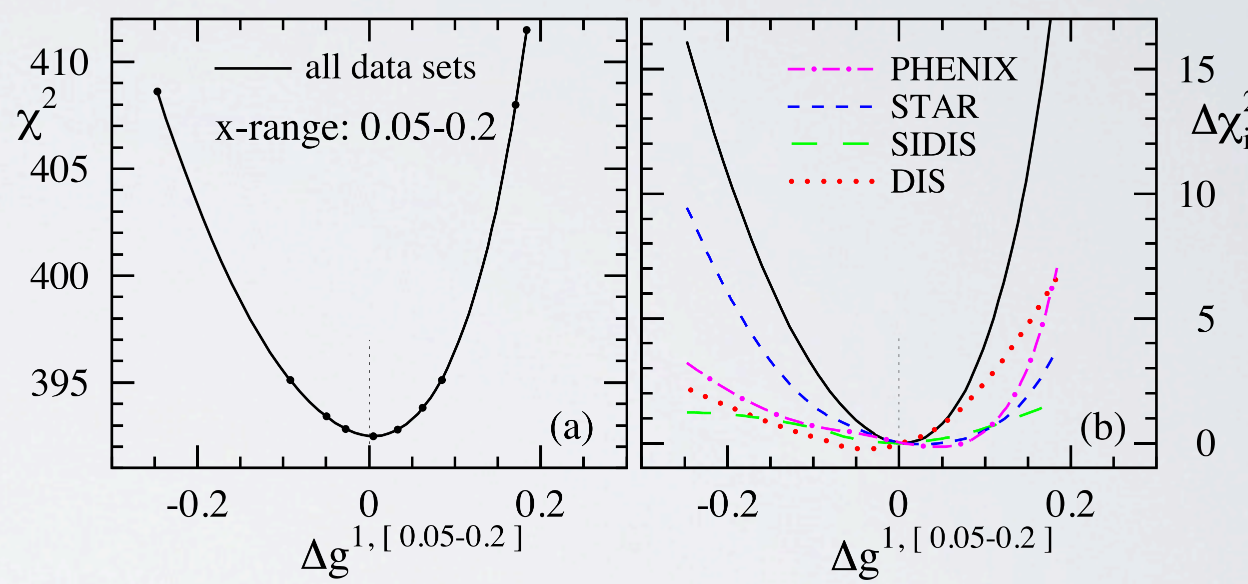
DSSV gluons

$$\Delta f_j^{1,[x_{\min}-x_{\max}]}(Q^2) \equiv \int_{x_{\min}}^{x_{\max}} \Delta f_j(x,Q^2)\,dx$$

Split in 3 regions

$$\begin{cases} 0.001 - 0.05 & \text{small x} \\ 0.05 - 0.2 & \text{'RHIC'} \\ 0.2 - 1 & \text{large x} \end{cases}$$





Complementarity of different data sets
RHIC mainly in [0.05-0.2] region

no clear statement for first moment : ~0
but huge uncertainty at small x

Δg rather small
even moderate
estimates (DNS/GRSV)
ruled out

3.4 Compass SIDIS update: DSSV+

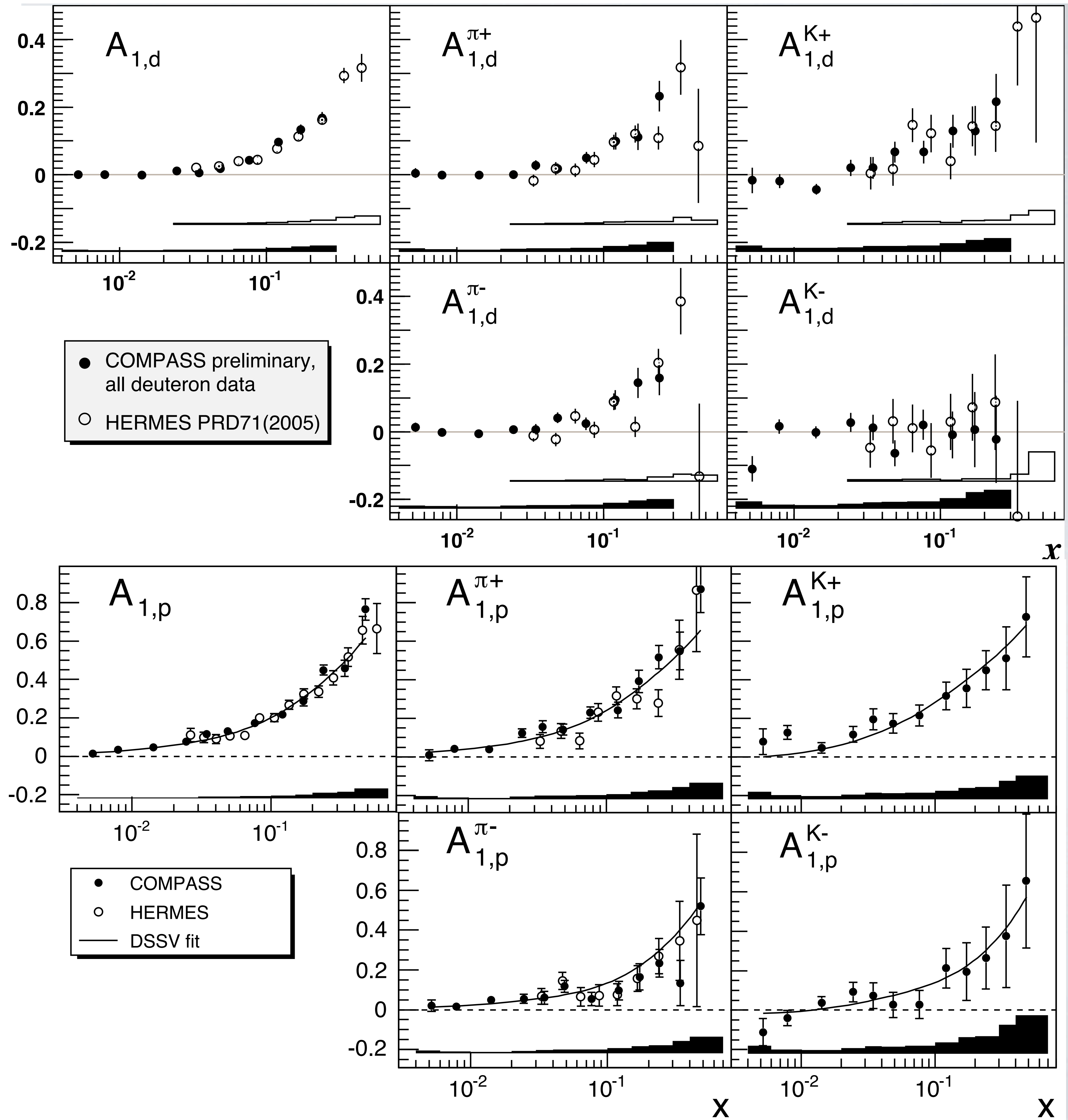
low x SIDIS

$\mu+(p,d)\rightarrow(\pi,K)+X$

DIS at low-x

DIS at high Q^2

M.G. Alekseev et al.,
Phys.Lett.B680:217-224,2009.



M.G. Alekseev et al.,
Phys.Lett.B693:227-235,2010

3.4 Compass SIDIS update: DSSV+

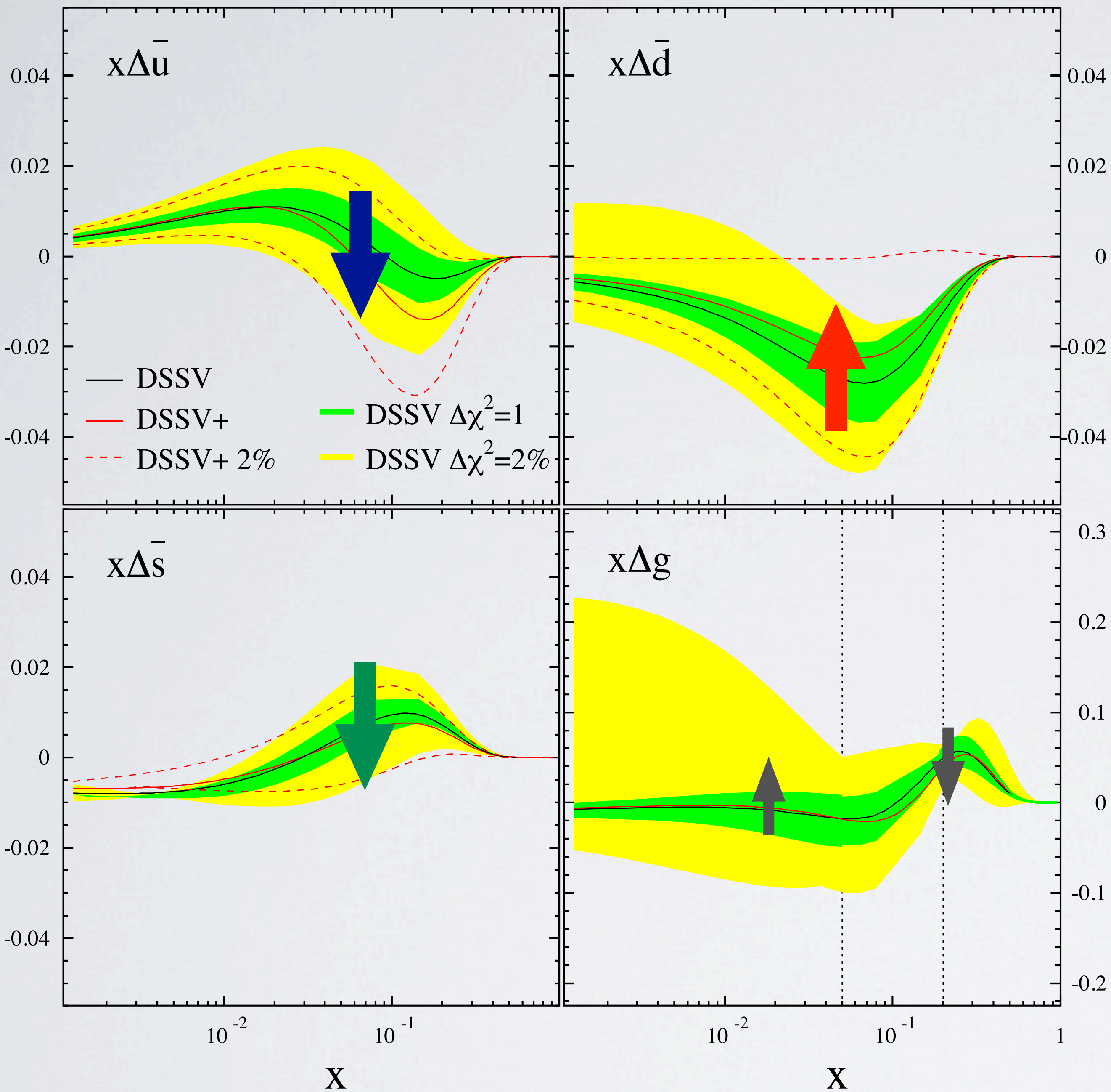
	(467)	+d data (44 new)	+d&p data (88 new)
DSSV	392.50	420.85	456.40
DSSV+		418.95	452.98
		~2 units	~4 units

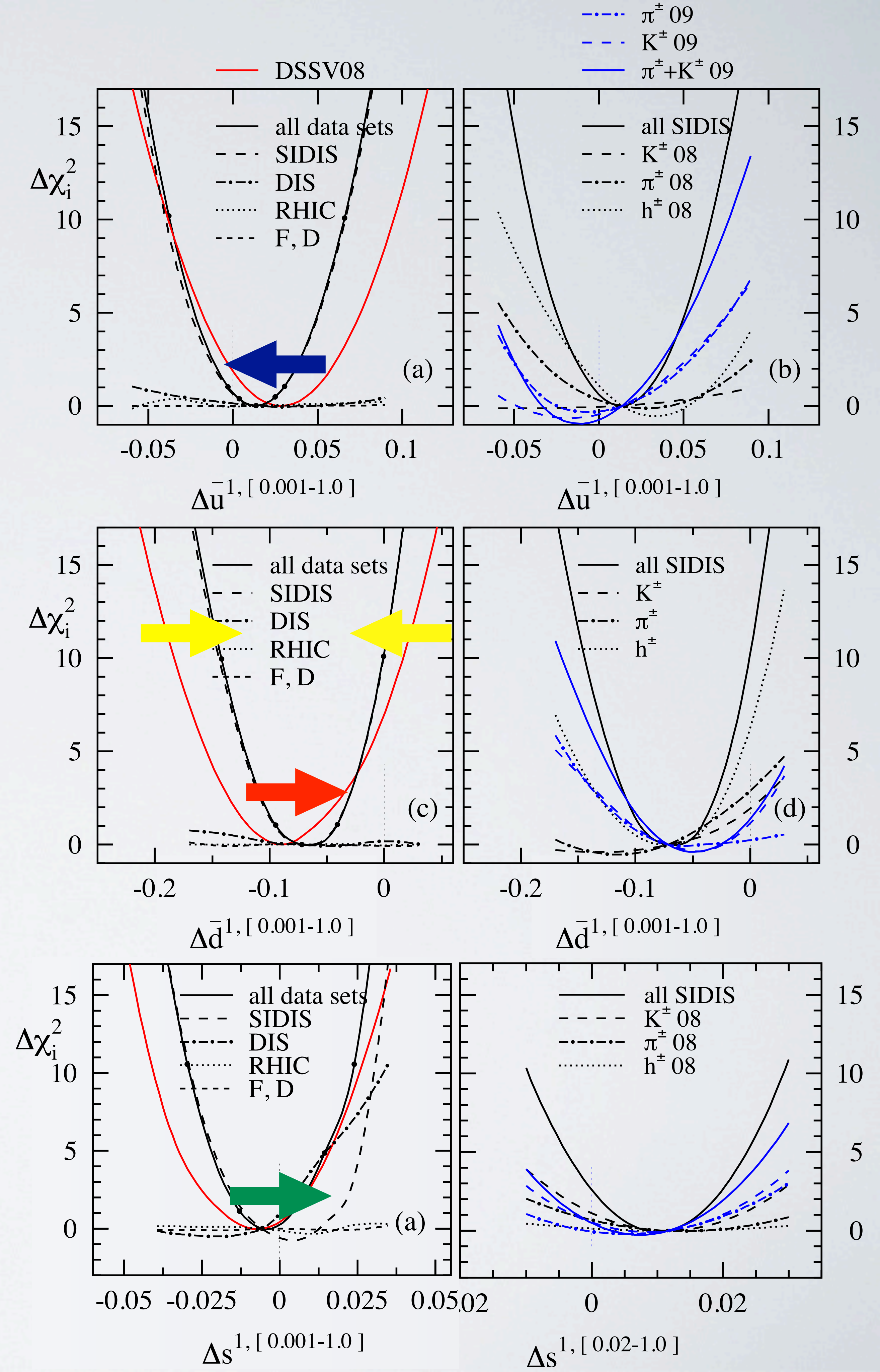
DSSV well within the error bars of DSSV+

$\Delta\chi^2=1$ is too small

$\Delta\chi^2=2\%$ is too much

3.4 Compass SIDIS update:





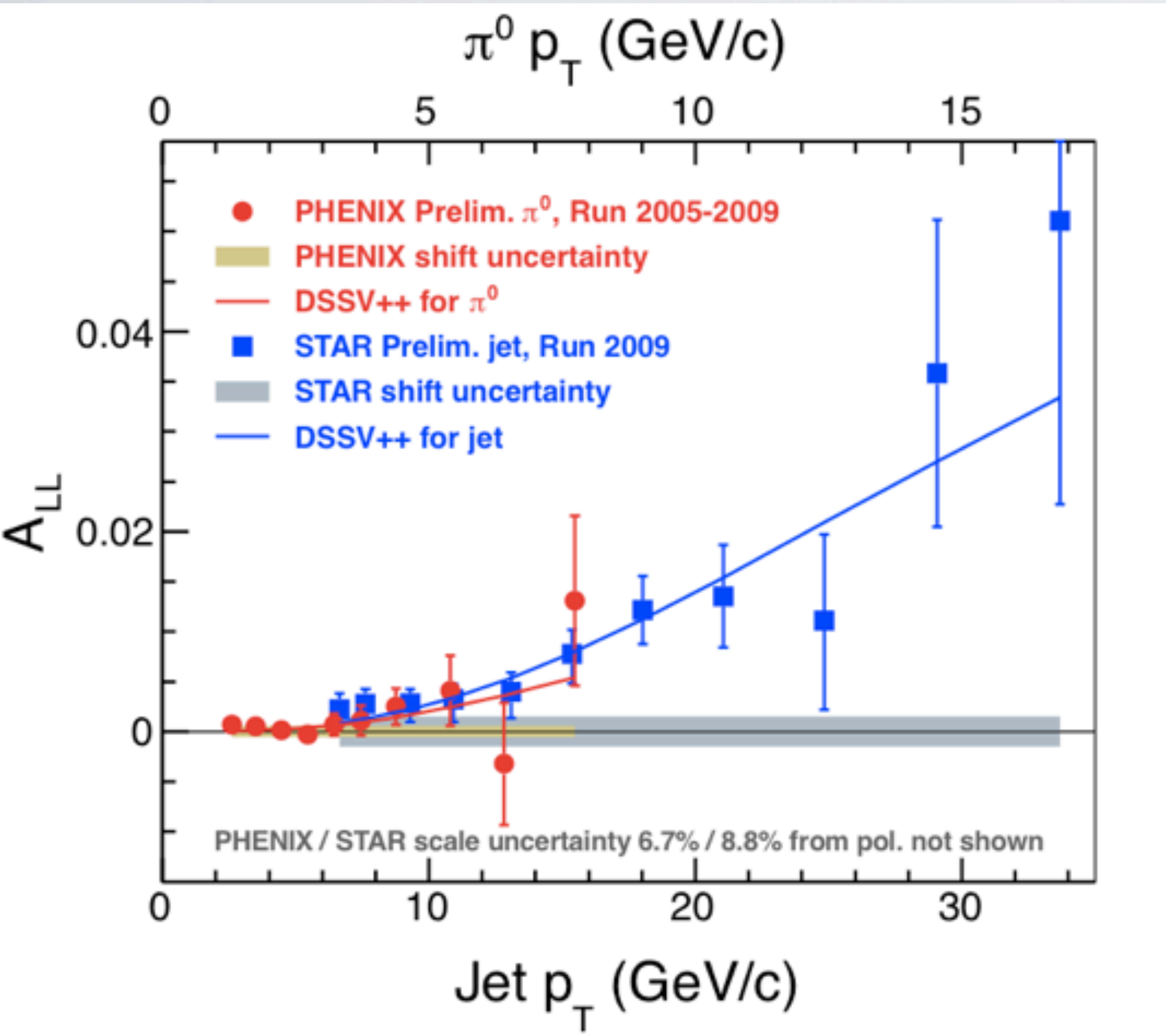
re-fit is well within DSSV bands ✔

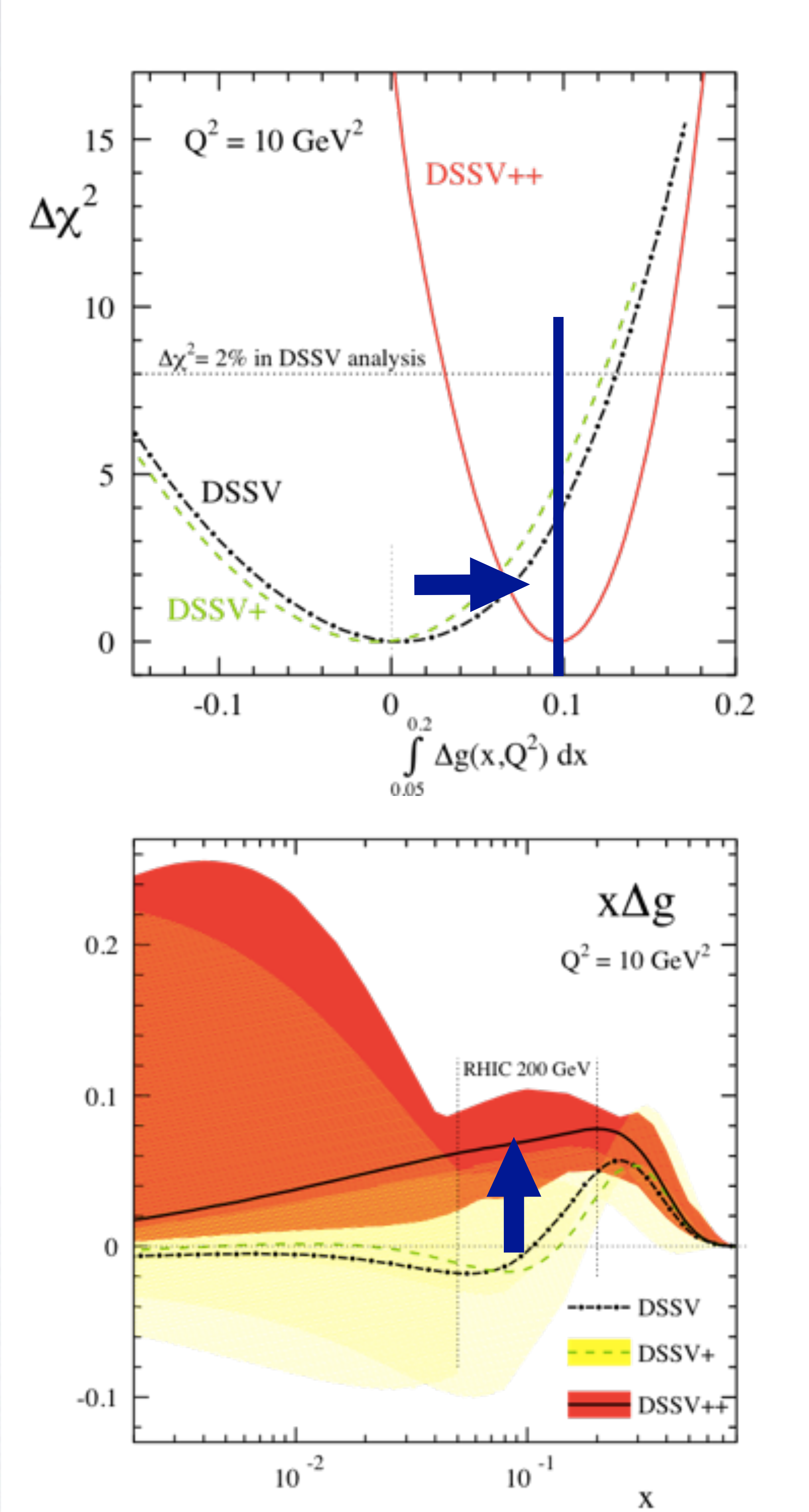
very minor shifts in moments — *shifts in the minima of the parabolae*

some shrinkage in the bands — *reduction of width of the parabolae*

3.5 RHIC preliminary/projections

DSSV++

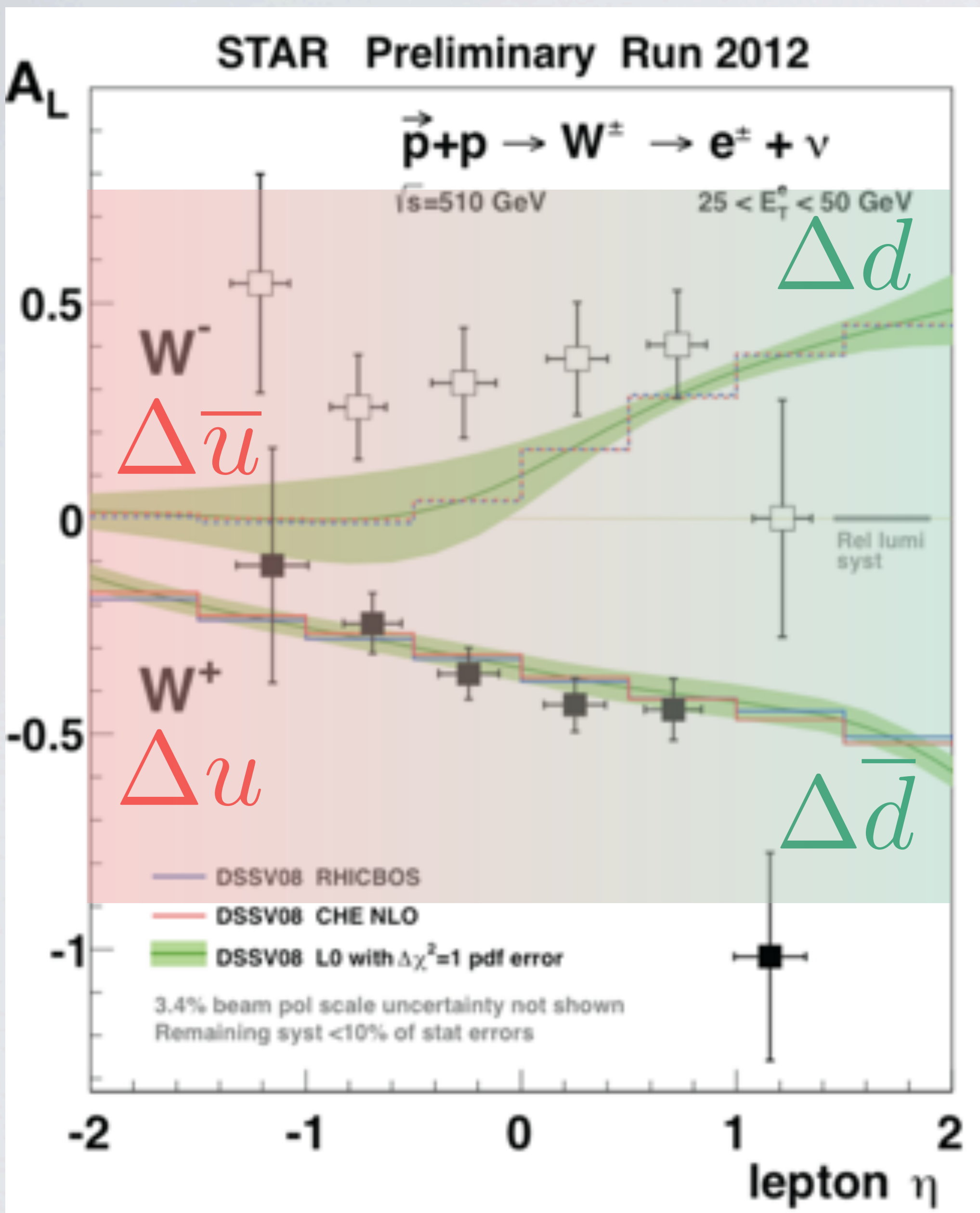


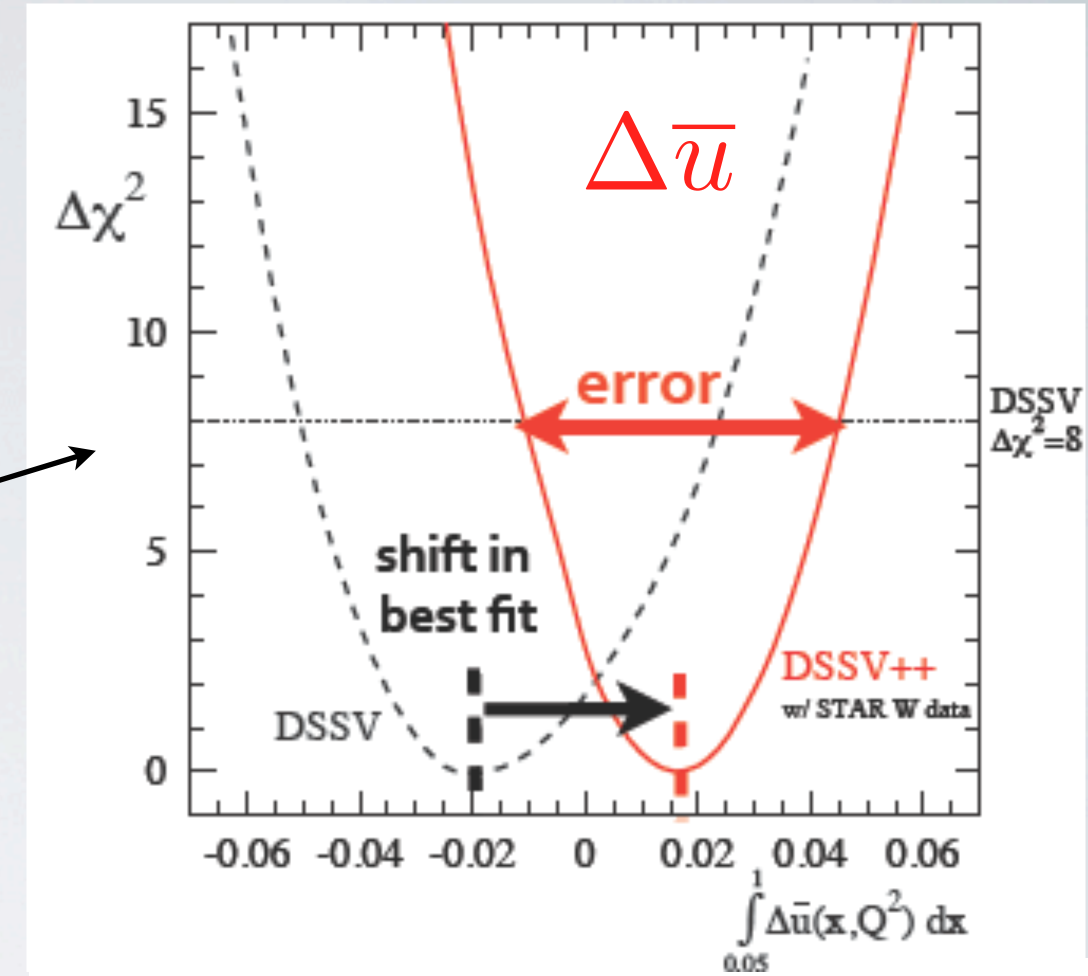


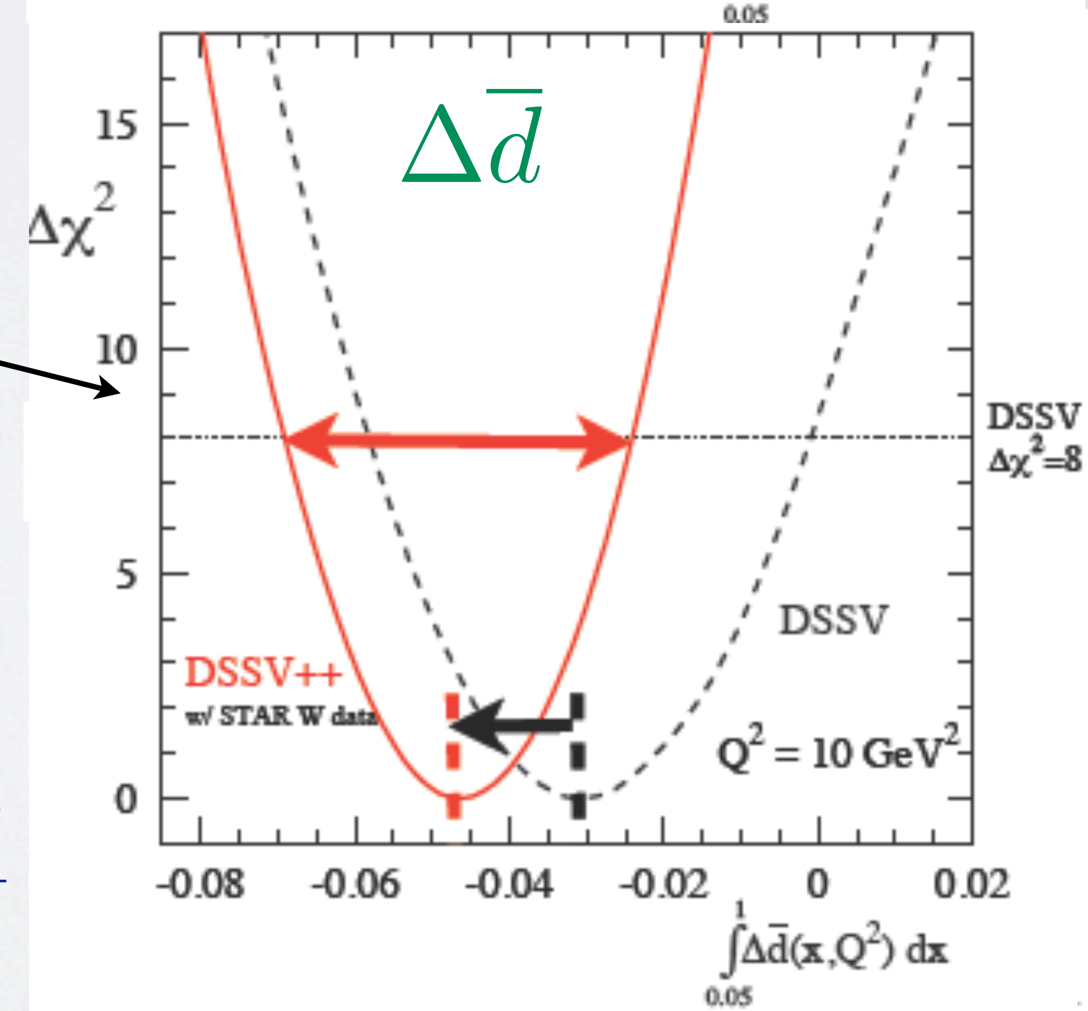
larger gluon polarization? (within errors)

3.5 RHIC preliminary/projections

DSSV++ w/STAR W





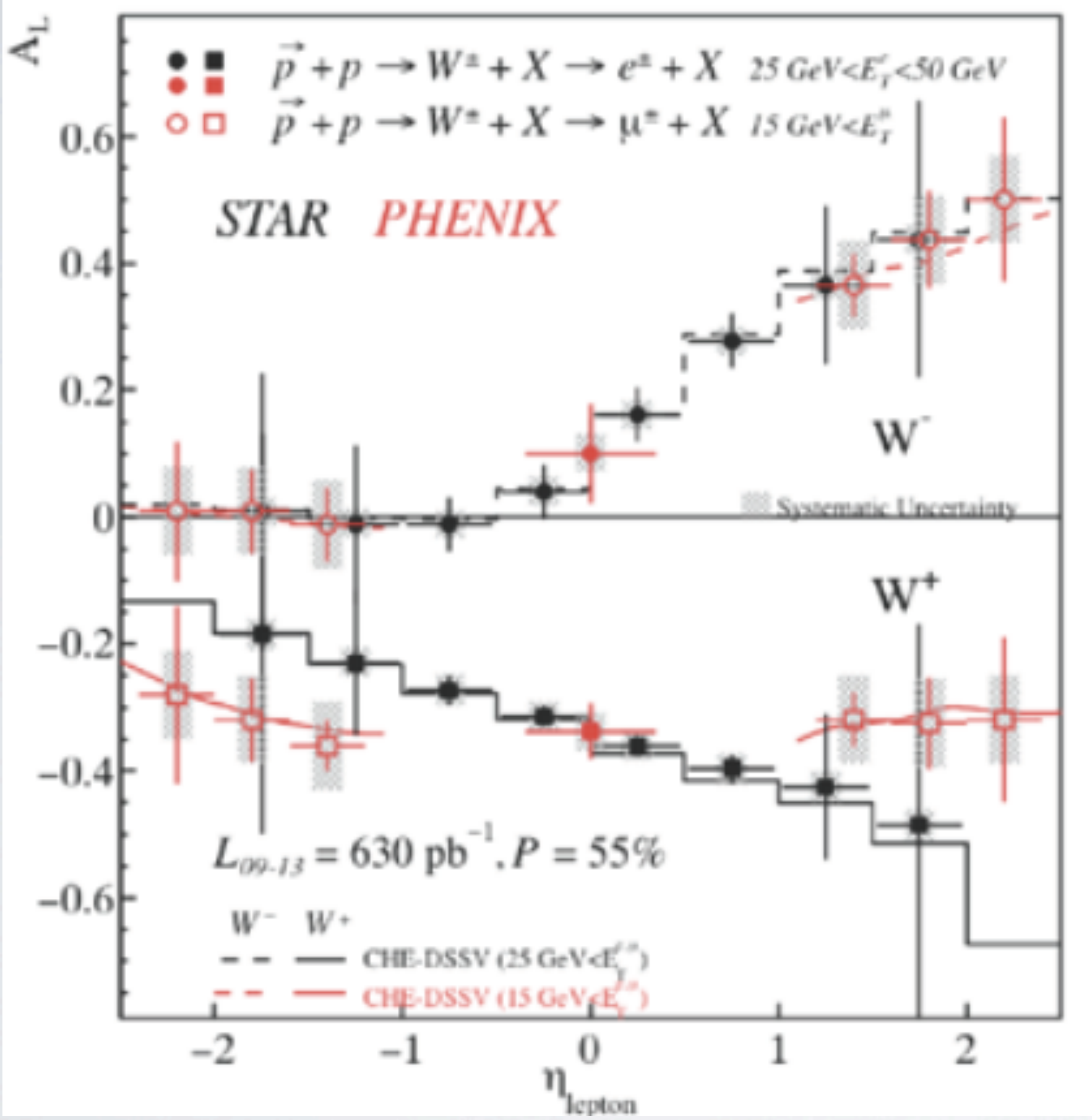


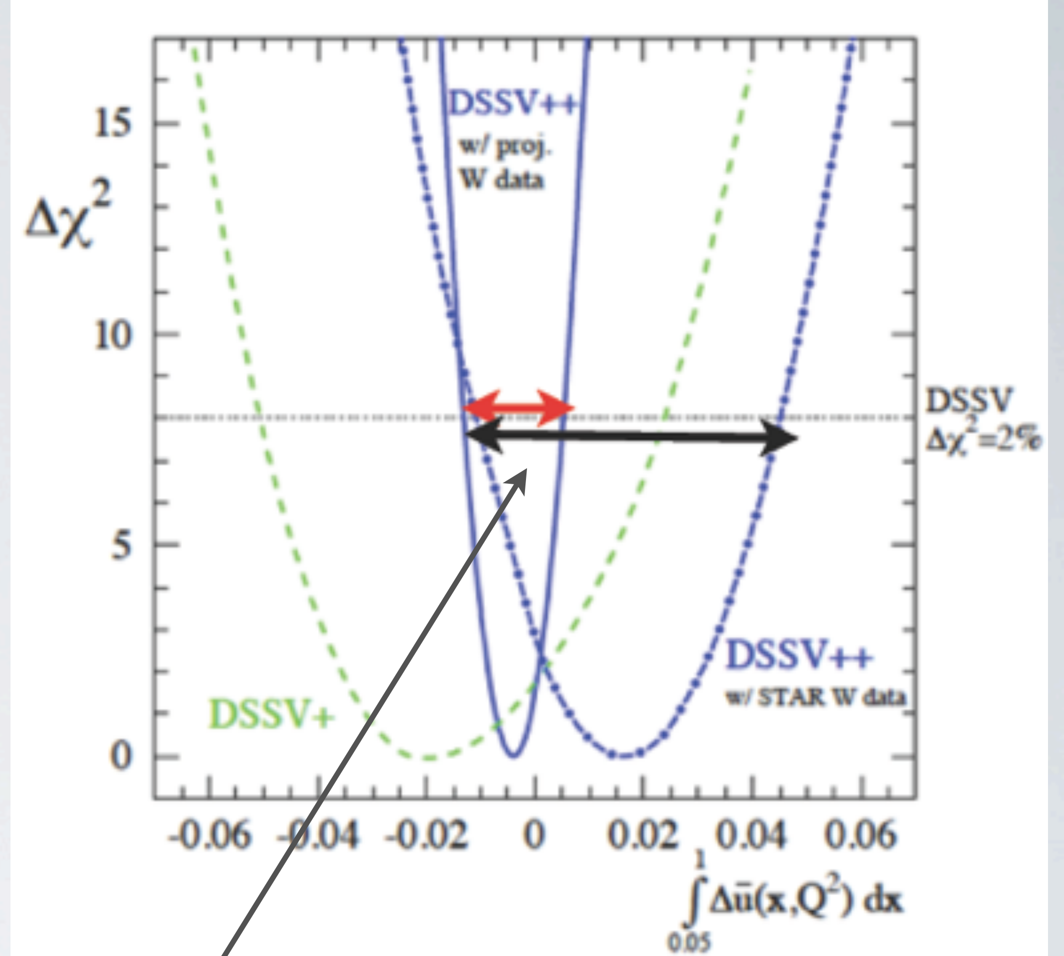
backward *forward*

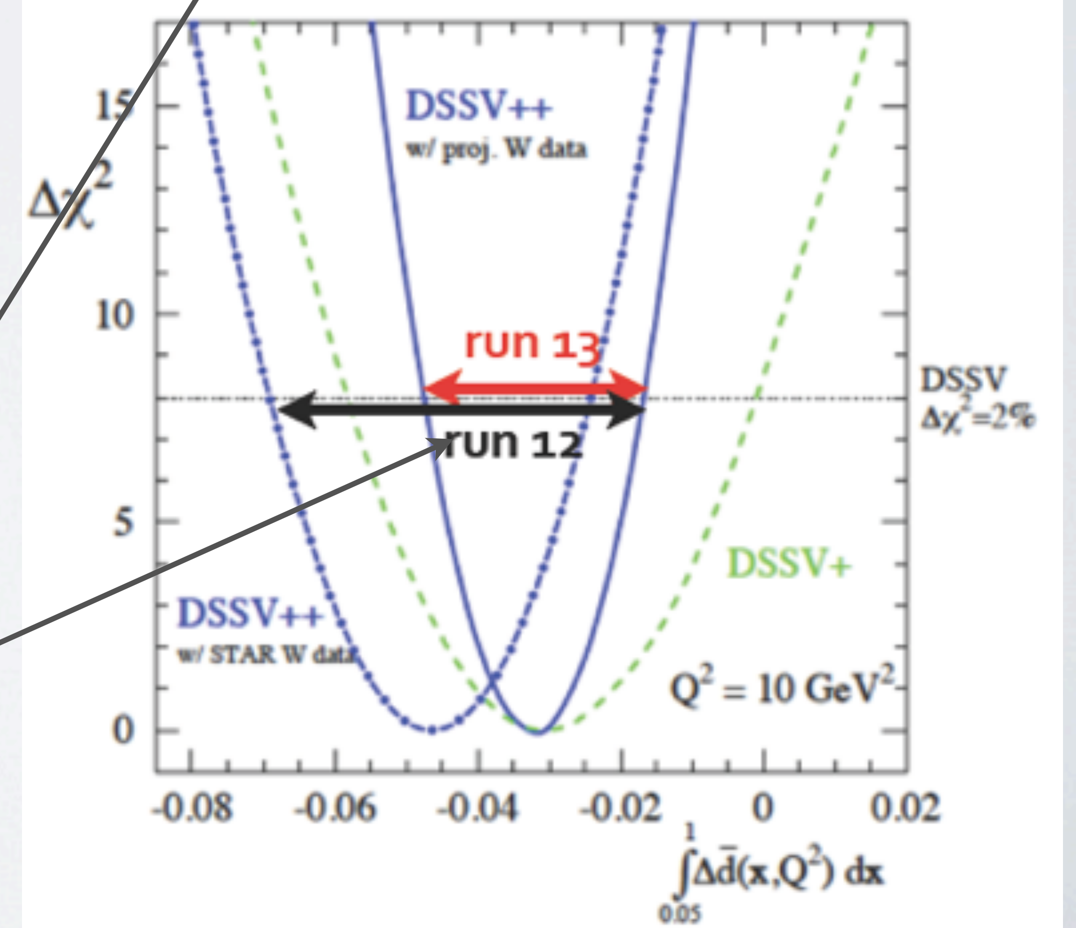
$$A_L^{e^-} \sim \frac{\Delta\overline{u}(x_a)d(x_b)(1-\cos\theta)^2 - \Delta d(x_a)\overline{u}(x_b)(1+\cos\theta)^2}{\overline{u}(x_a)d(x_b)(1-\cos\theta)^2 + d(x_a)\overline{u}(x_b)(1+\cos\theta)^2}$$

3.5 RHIC preliminary/projections

projections







significant reduction of uncertainties

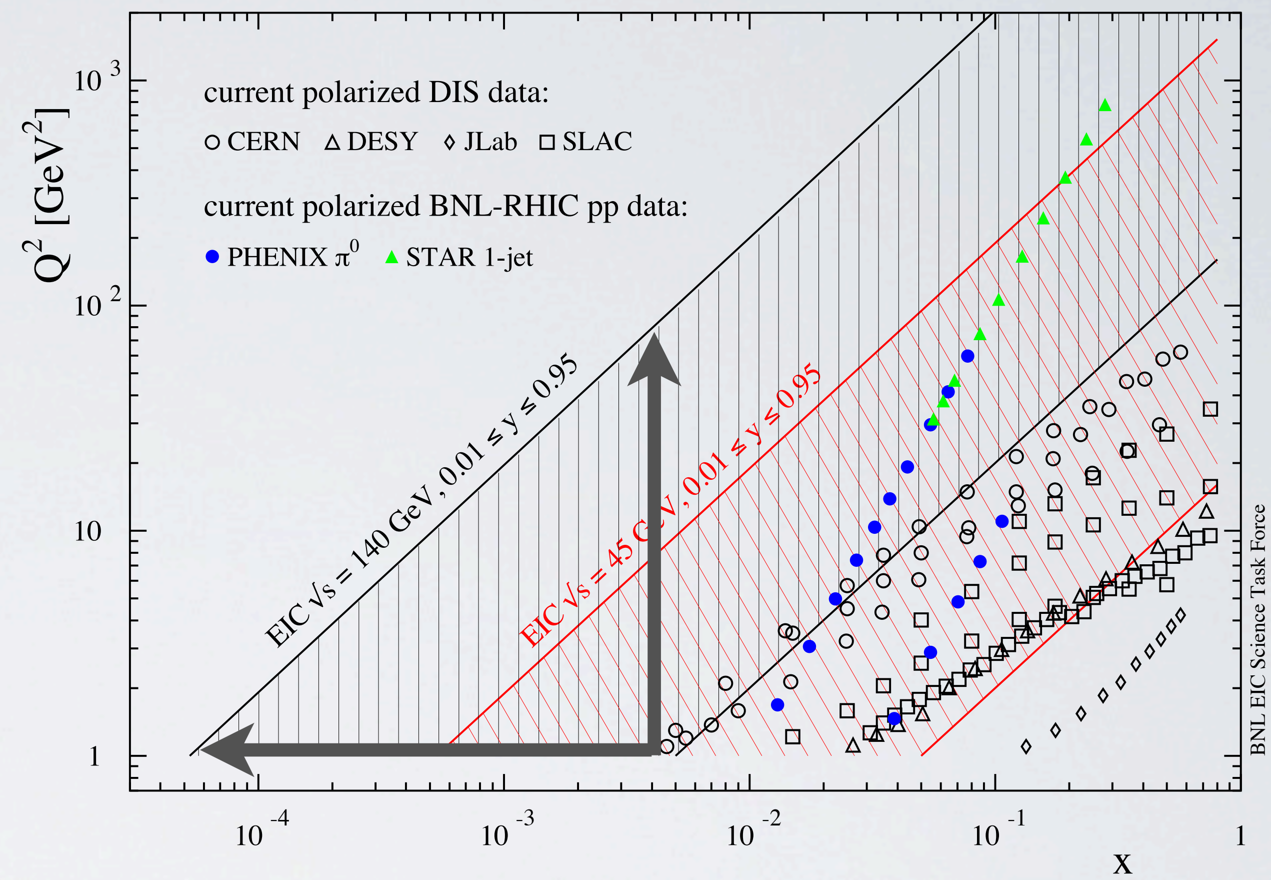
SIDIS & FFs cross check

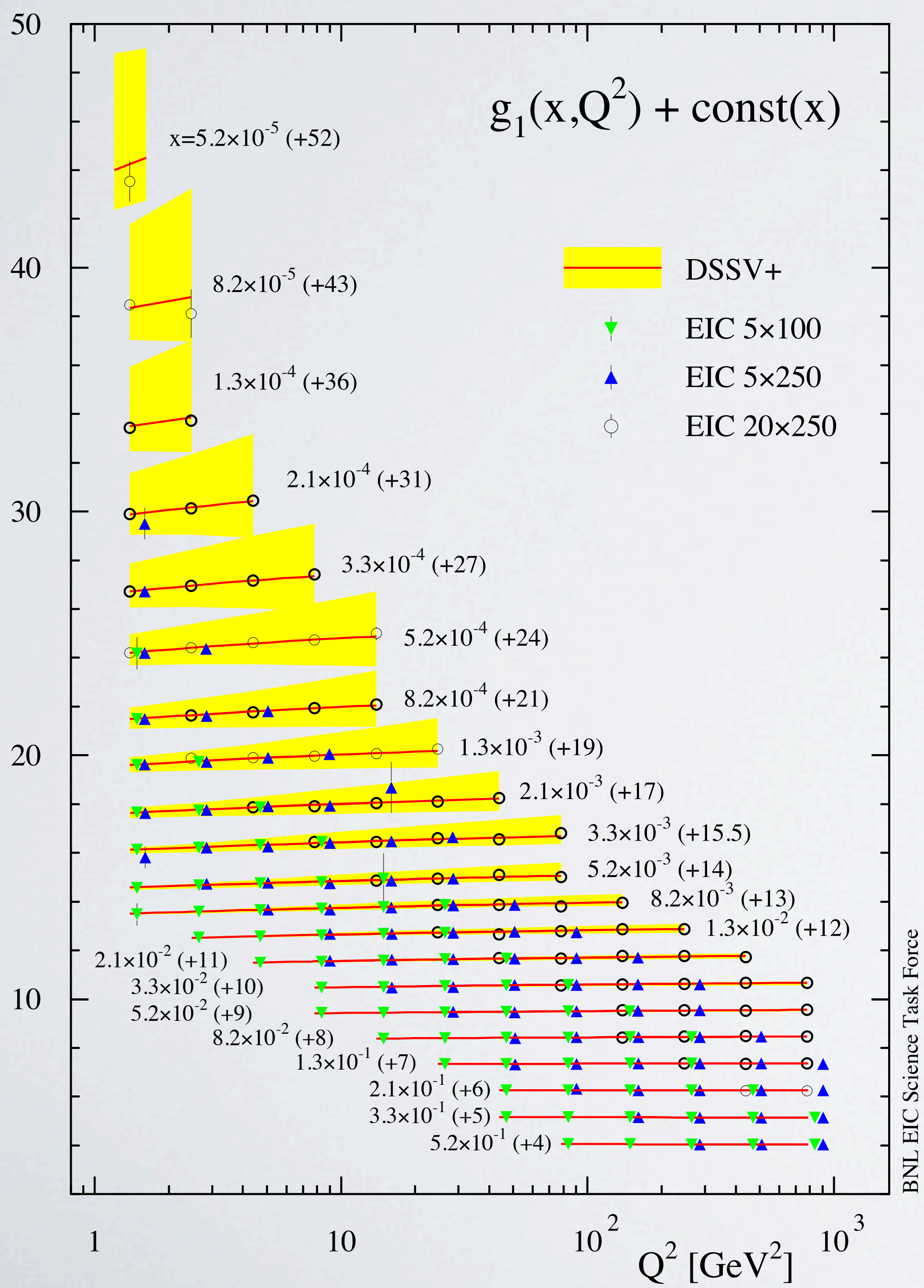
3.6 EIC projections

Aschenauer, R.S., Stratmann 1209.3240

EIC kinematic reach:

- two decades in x
- large Q^2 coverage



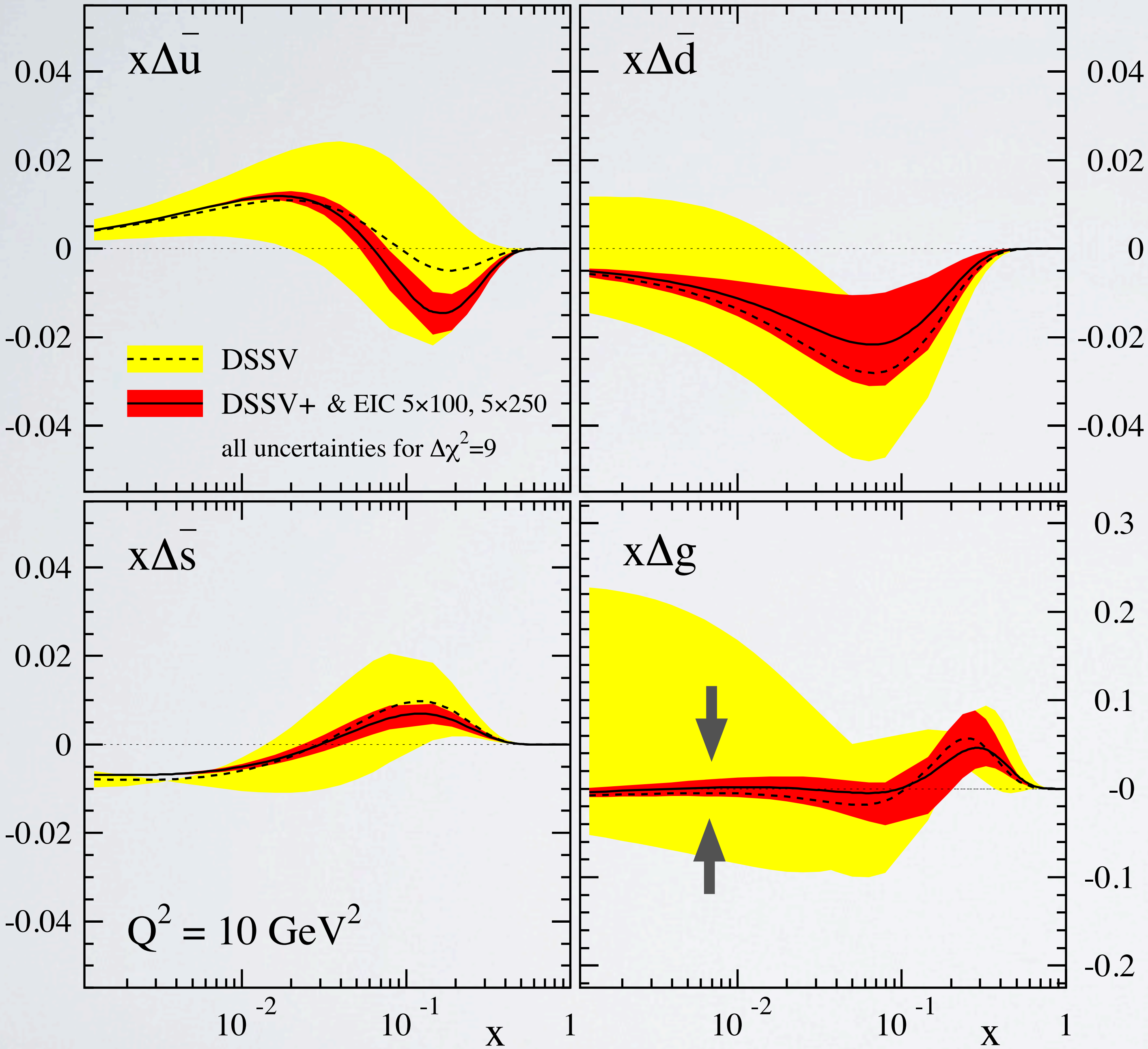


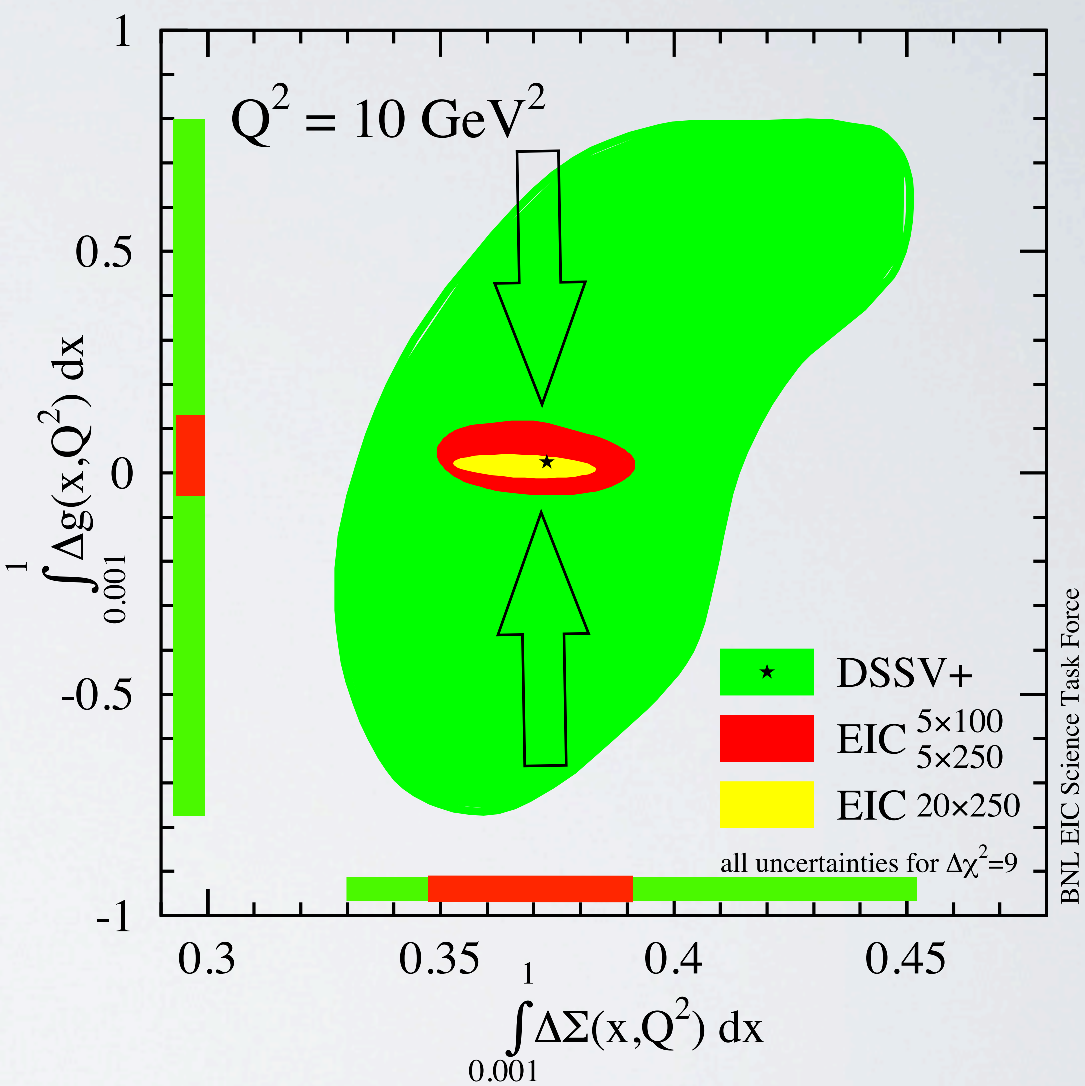
- precise DIS & SIDIS
- low-x
- Δg from scaling violations
- charged current DIS

3.6 EIC projections

Aschenauer, R.S., Stratmann 1209.3240

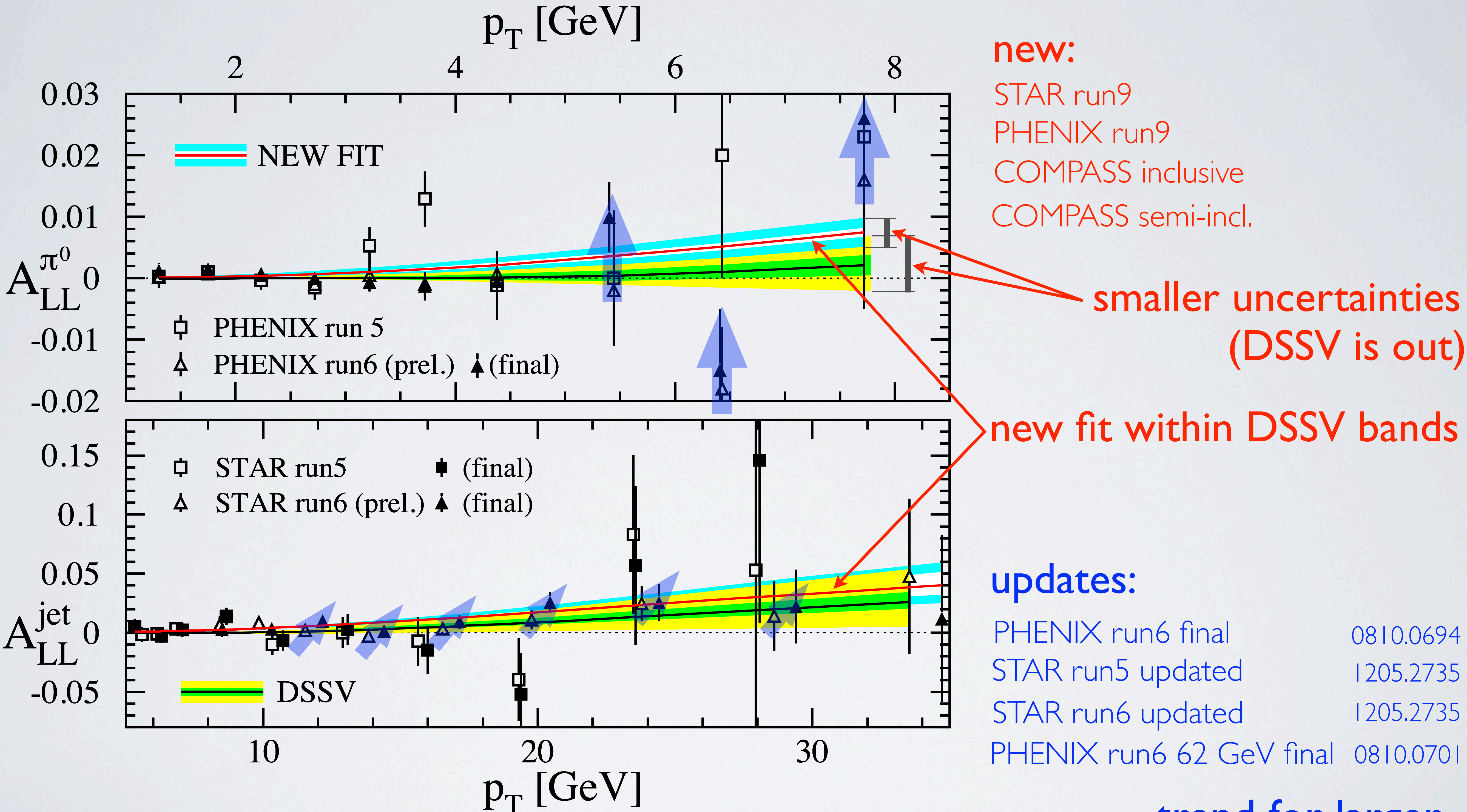
Impact from DIS & SIDIS





3.7 DSSV gluon update

de Florian, R.S., Stratmann, Vogelsang 1404.4293



new:

- STAR run9
- PHENIX run9
- COMPASS inclusive
- COMPASS semi-incl.

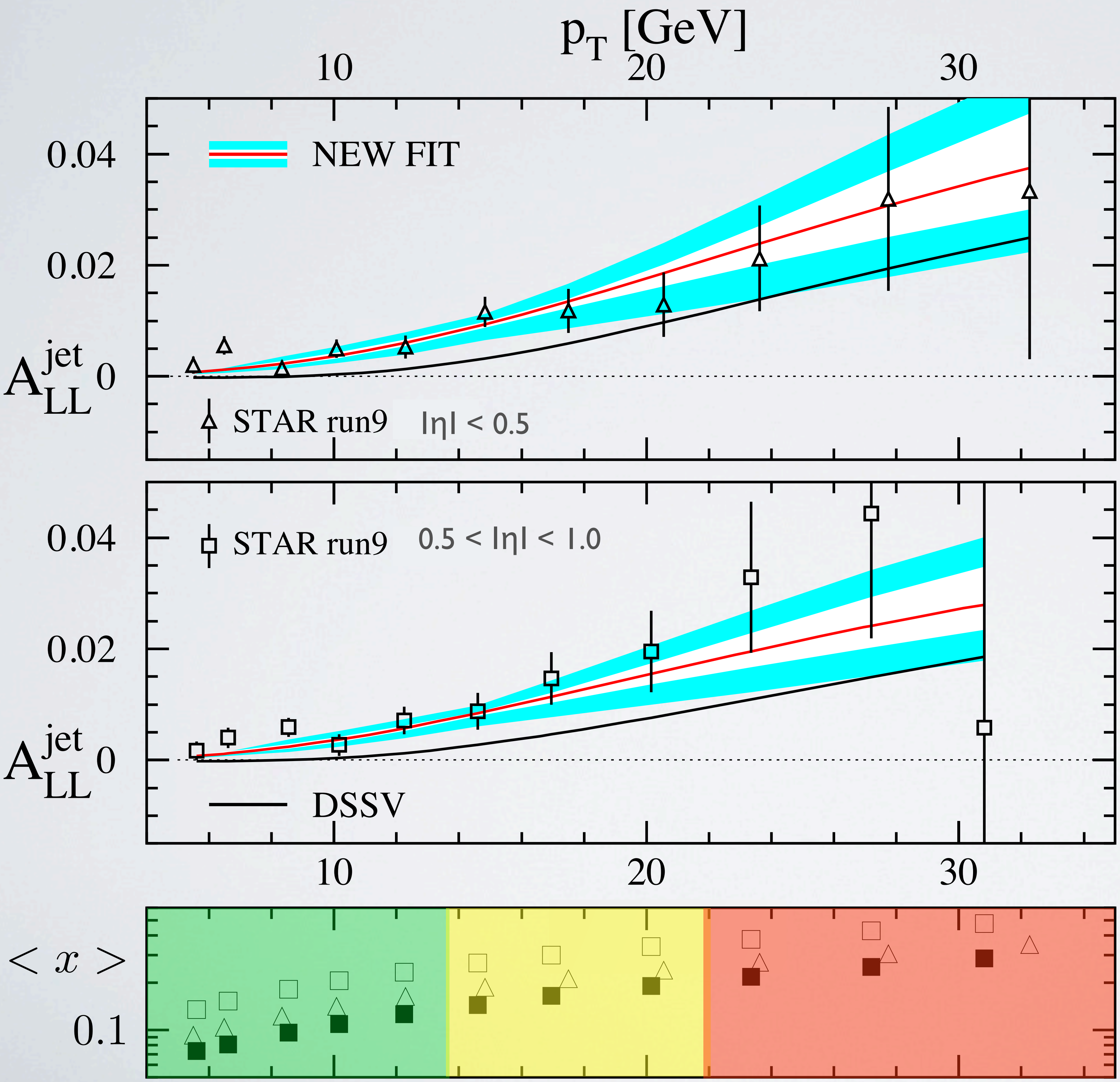
updates:

PHENIX run6 final	0810.0694
STAR run5 updated	1205.2735
STAR run6 updated	1205.2735
PHENIX run6 62 GeV final	0810.0701

trend for larger asymmetries

3.7 DSSV gluon update

de Florian, R.S., Stratmann, Vogelsang 1404.4293



anti-k_T jets

$$d_{ij} = min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{T,i}^{2p}$$

two rapidity ranges

|η| < 0.5

0.5 < |η| < 1.0

➡ x-dependence

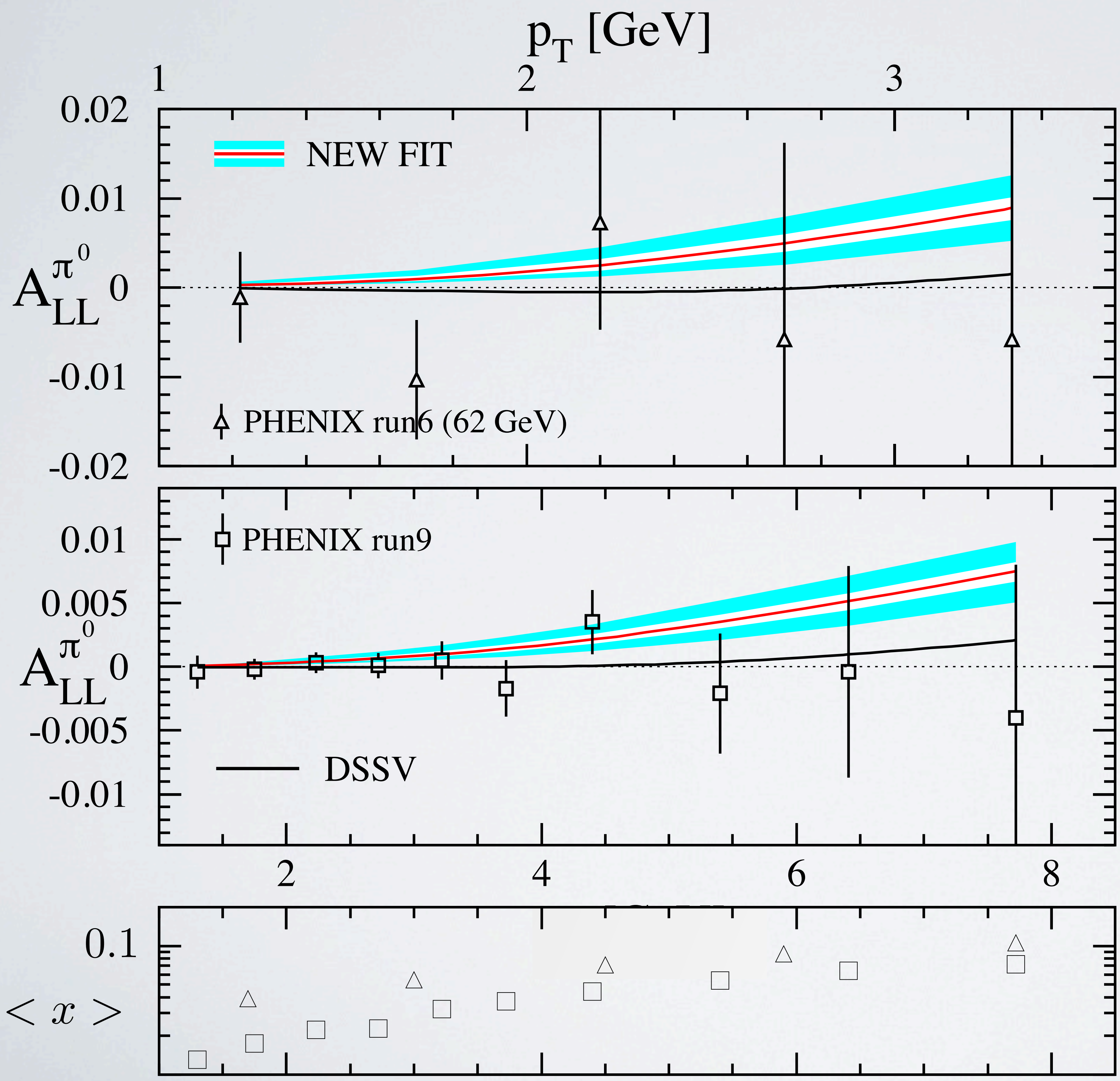
higher precision (scale X3)

➡ higher-x probe

above DSSV

3.7 DSSV gluon update

de Florian, R.S., Stratmann, Vogelsang 1404.4293



prefer DSSV?

negative helicity?

3.7 DSSV gluon update

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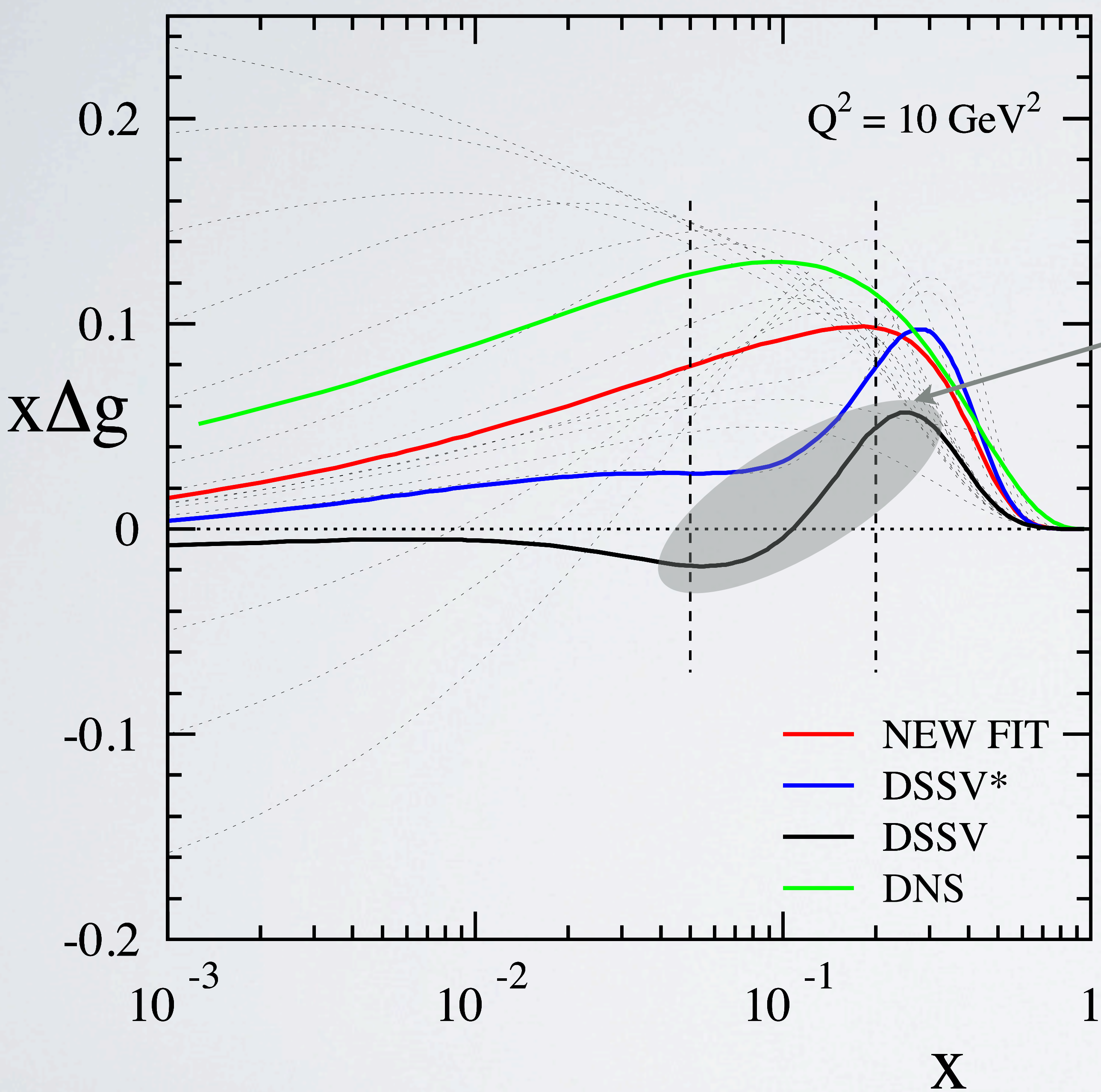
The gluons



DSSV parameterization:

$$x\Delta g(x,\mu_0^2) = N_g\, x^{\alpha_g}(1-x)^{\beta_g}(1+\eta_g x^{\kappa_g})$$

$\eta_g \sim -4$

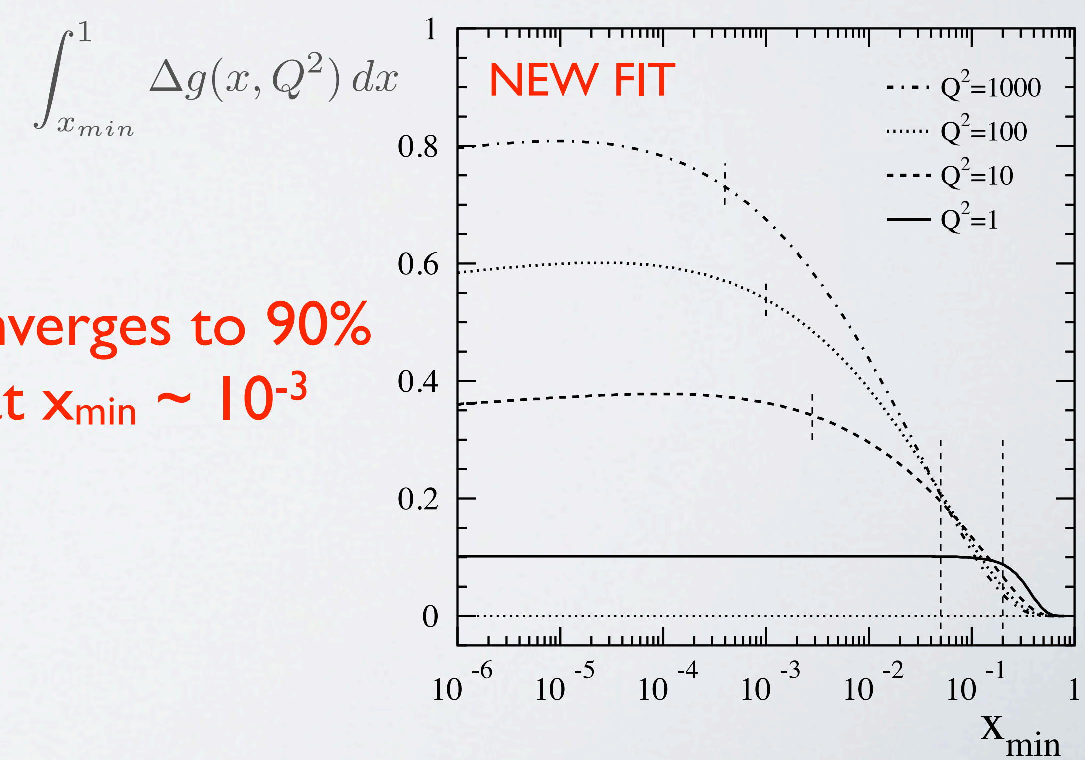
$\kappa_g \sim 1$

NEW FIT parameterization:

$\eta_g \sim 0.023$

$$x\Delta g(x,\mu_0^2) = N_g\, x^{\alpha_g}(1-x)^{\beta_g}(1+\eta_g x^{\kappa_g})$$

$\kappa_g \sim -3$



converges to 90% at $x_{min} \sim 10^{-3}$

3.7 DSSV gluon update

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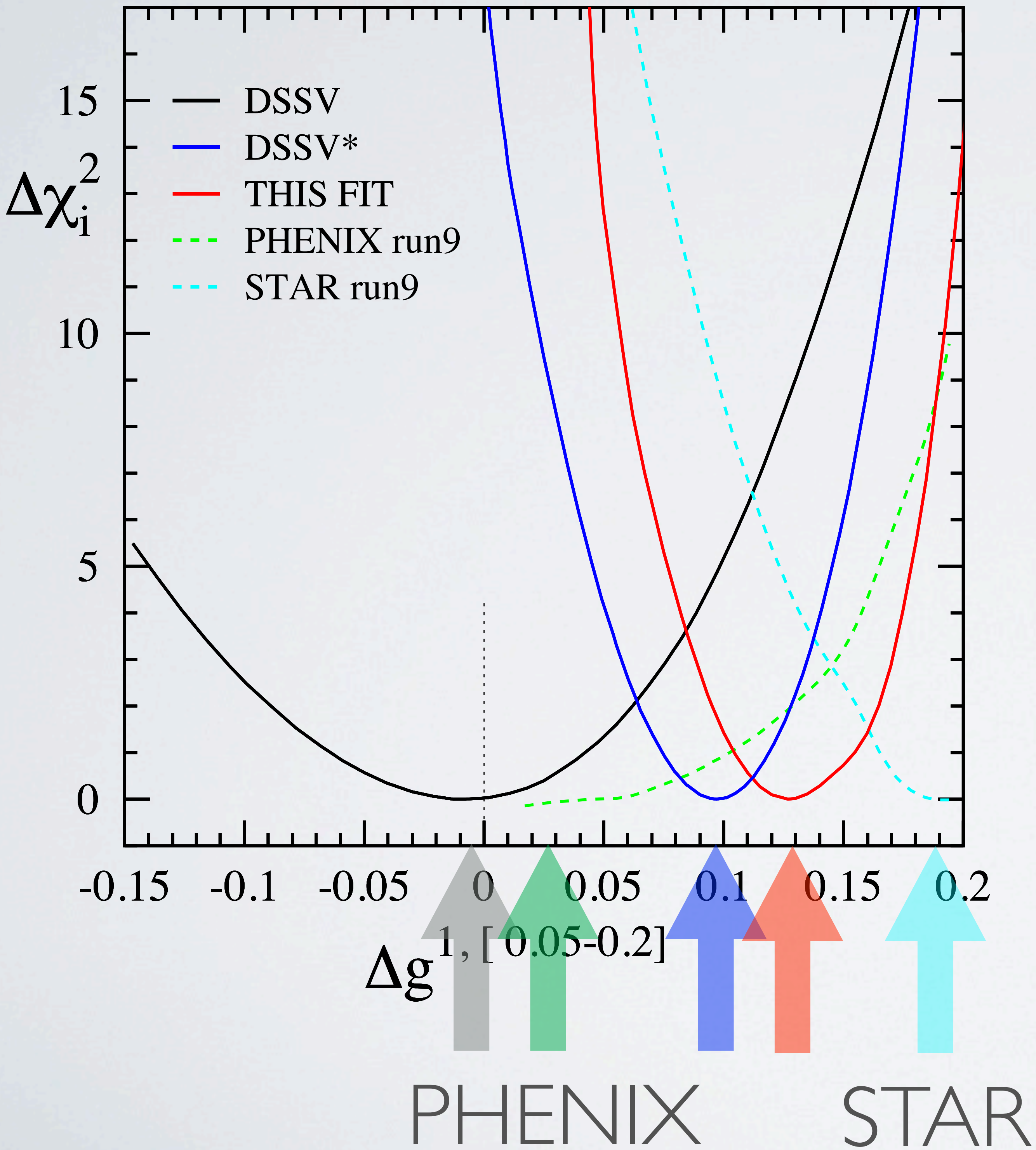
Truncated moments



$$\Delta g^{1,[0.05-0.2]}(Q^2) \equiv \int_{0.05}^{0.2} \Delta g(x, Q^2)\, dx$$

tension?

complementarity:
Q²-dependence

3.7 DSSV gluon update

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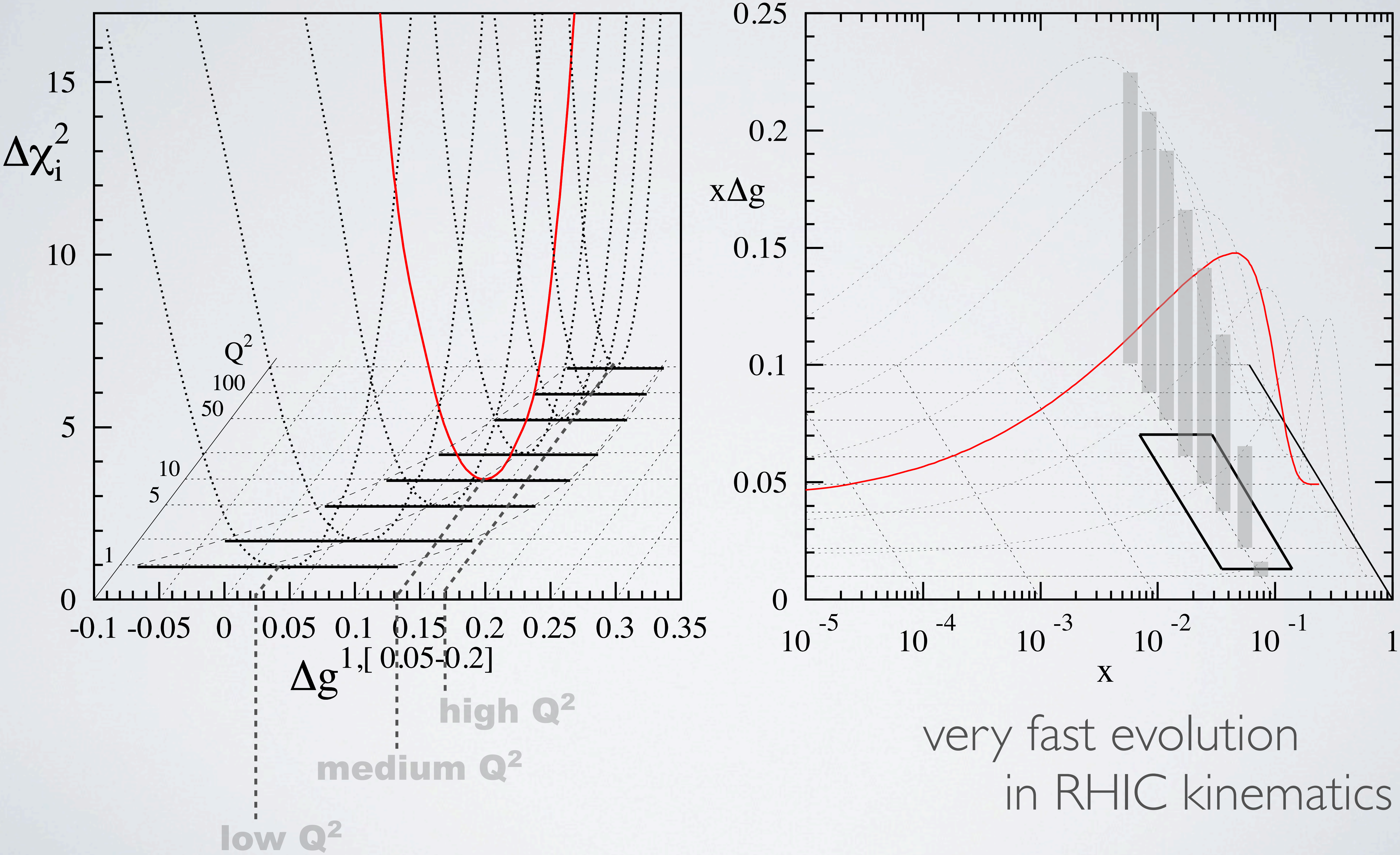
Q²-dependence



very fast evolution
in RHIC kinematics

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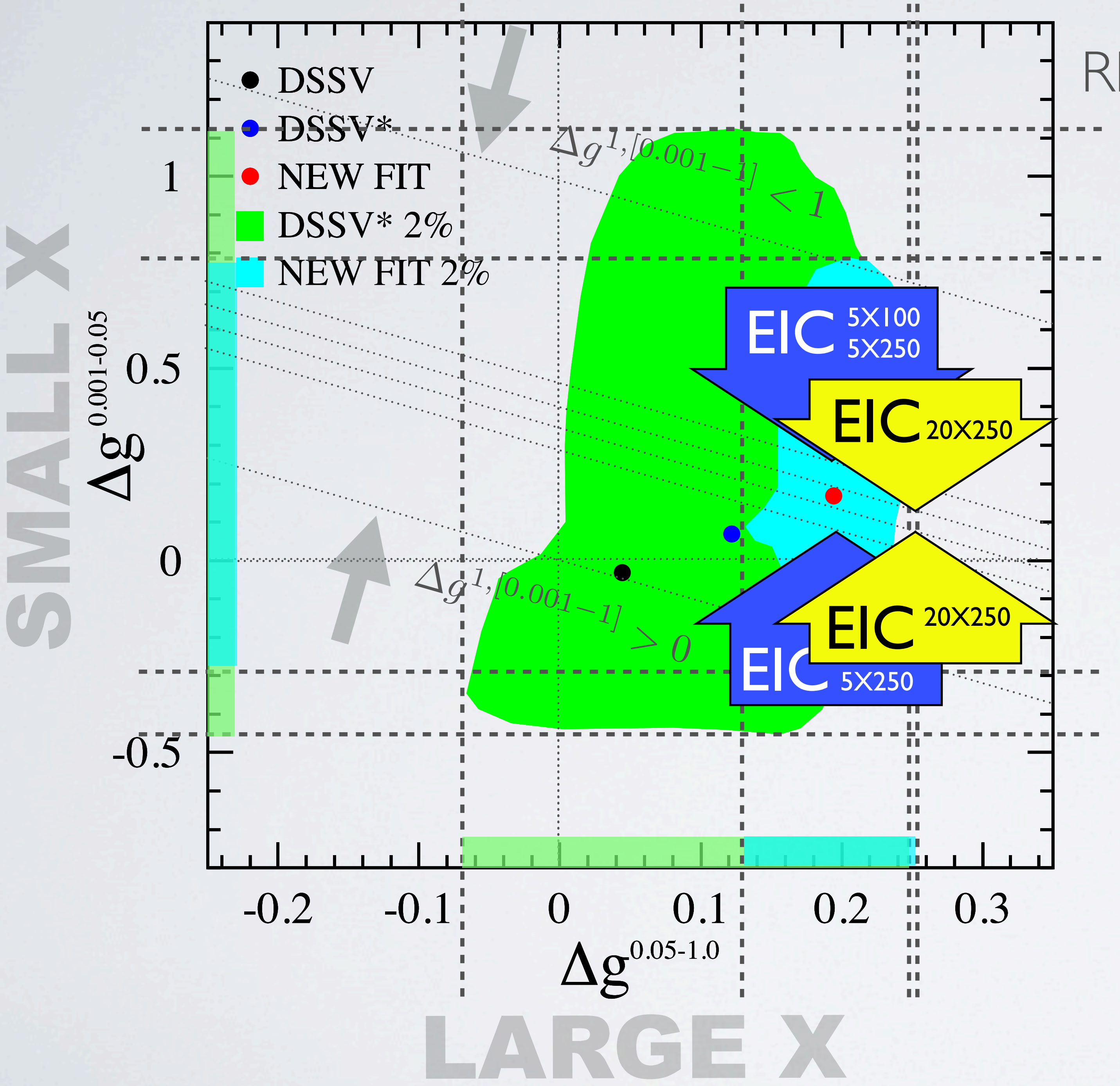
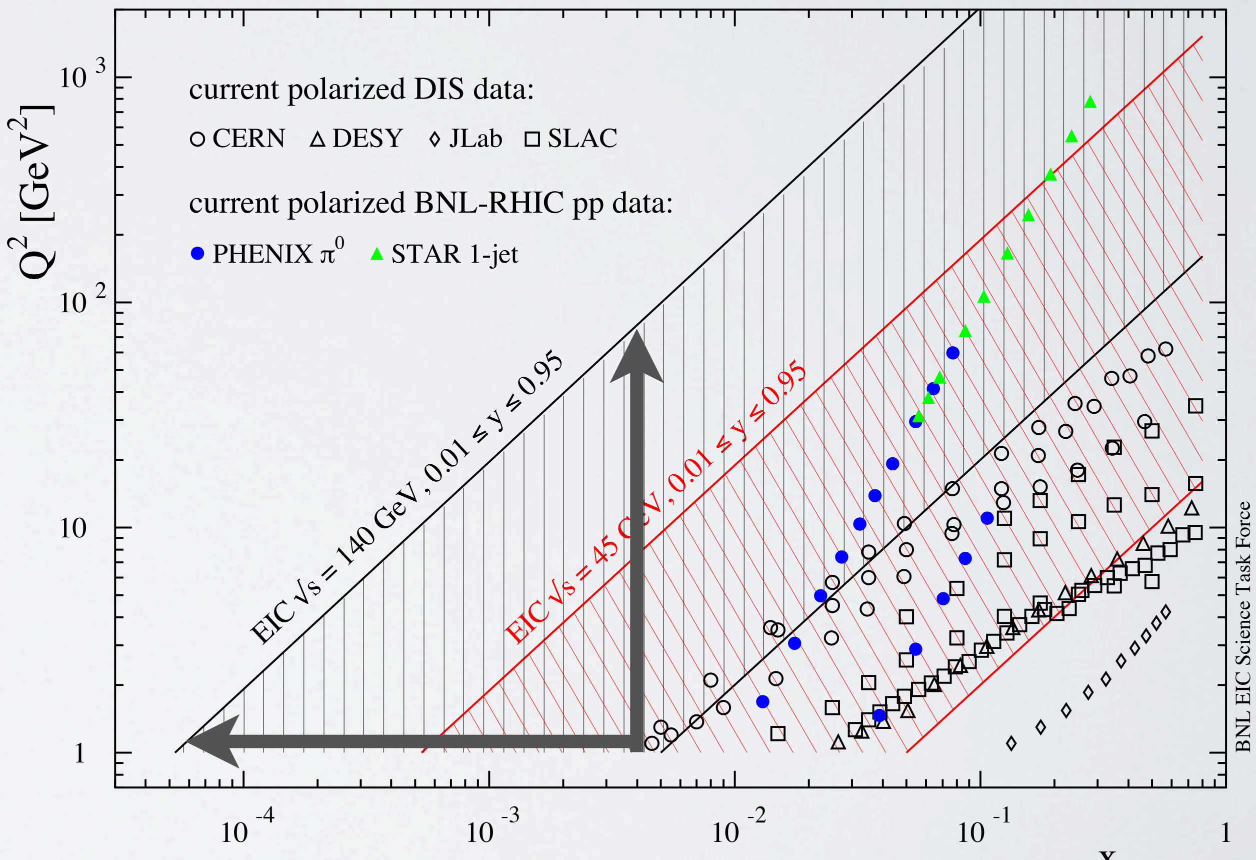
what about small and large-x?



RHIC probes a limited range in x, however...

EIC could extend two decades in x



ASCHENAUER, R.S., STRATMANN 1209.3240

3.7 DSSV gluon update

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how do we estimate errors?

can't use MSTW & CTEQ dynamical scheme

~ Improved Hessian

1. pick a *relevant observable* (not a parameter)

   ~ truncated moment

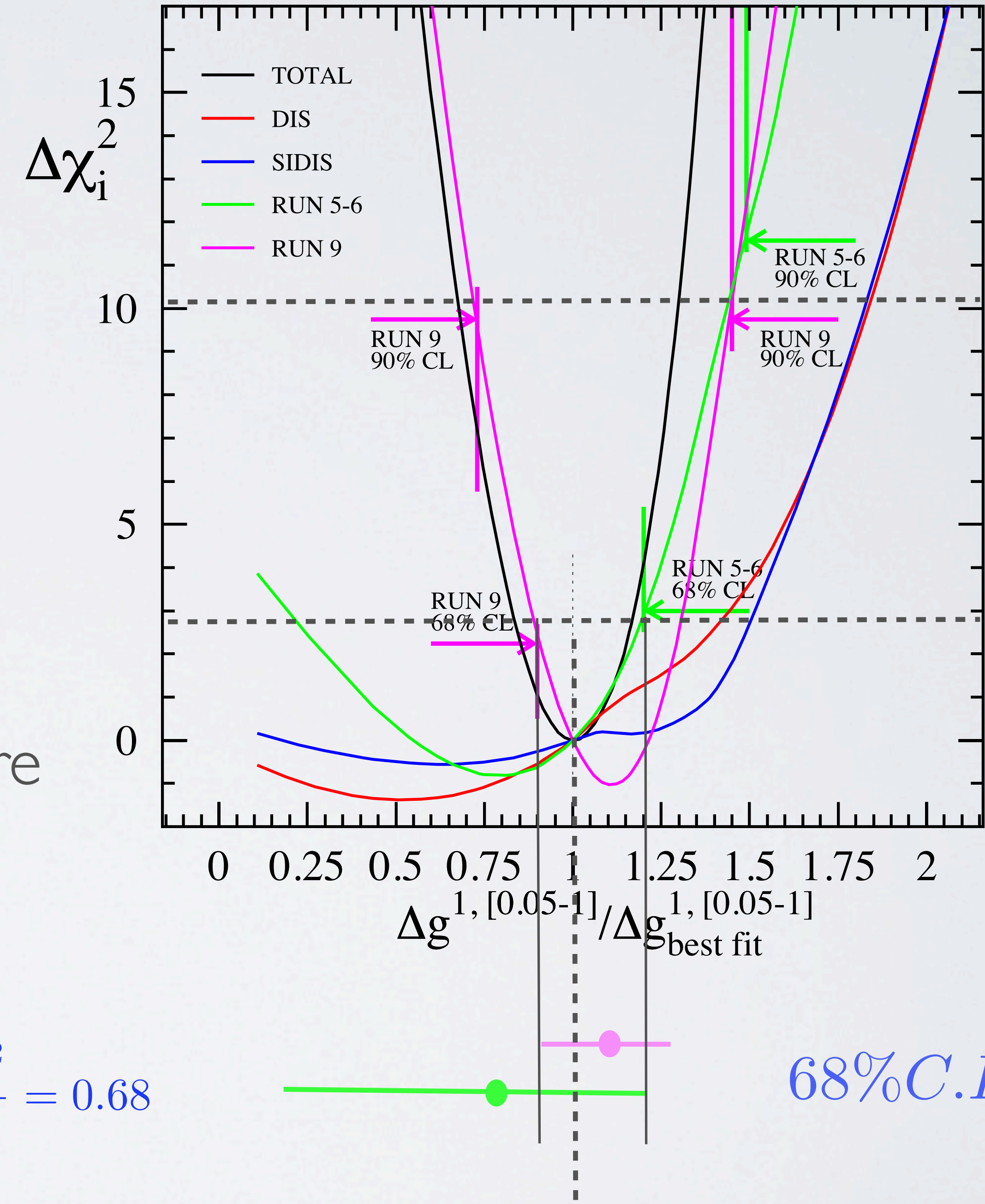
2. plot profiles for subsets of data

   ~ experiment, data set

3. check their own 68% and 90% CL limits

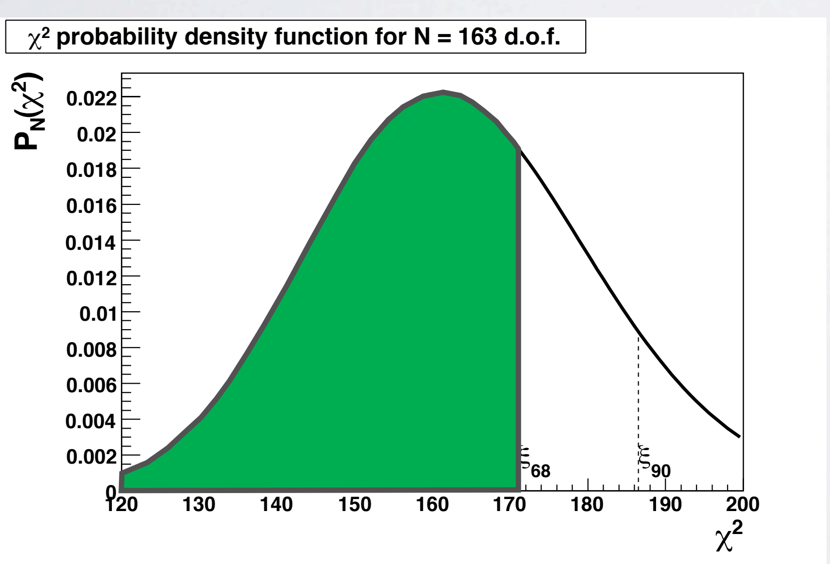
   ~ assume χ^2 distribution

4. read error and tolerance for largest departure



$$\int_0^{\xi_{68}} d\chi^2 \, \frac{(\chi^2)^{N/2-1} e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)} = 0.68$$

$68\% C.L.$



3.8 NNPDF reweighting

E. Nocera et al. 1406.5539

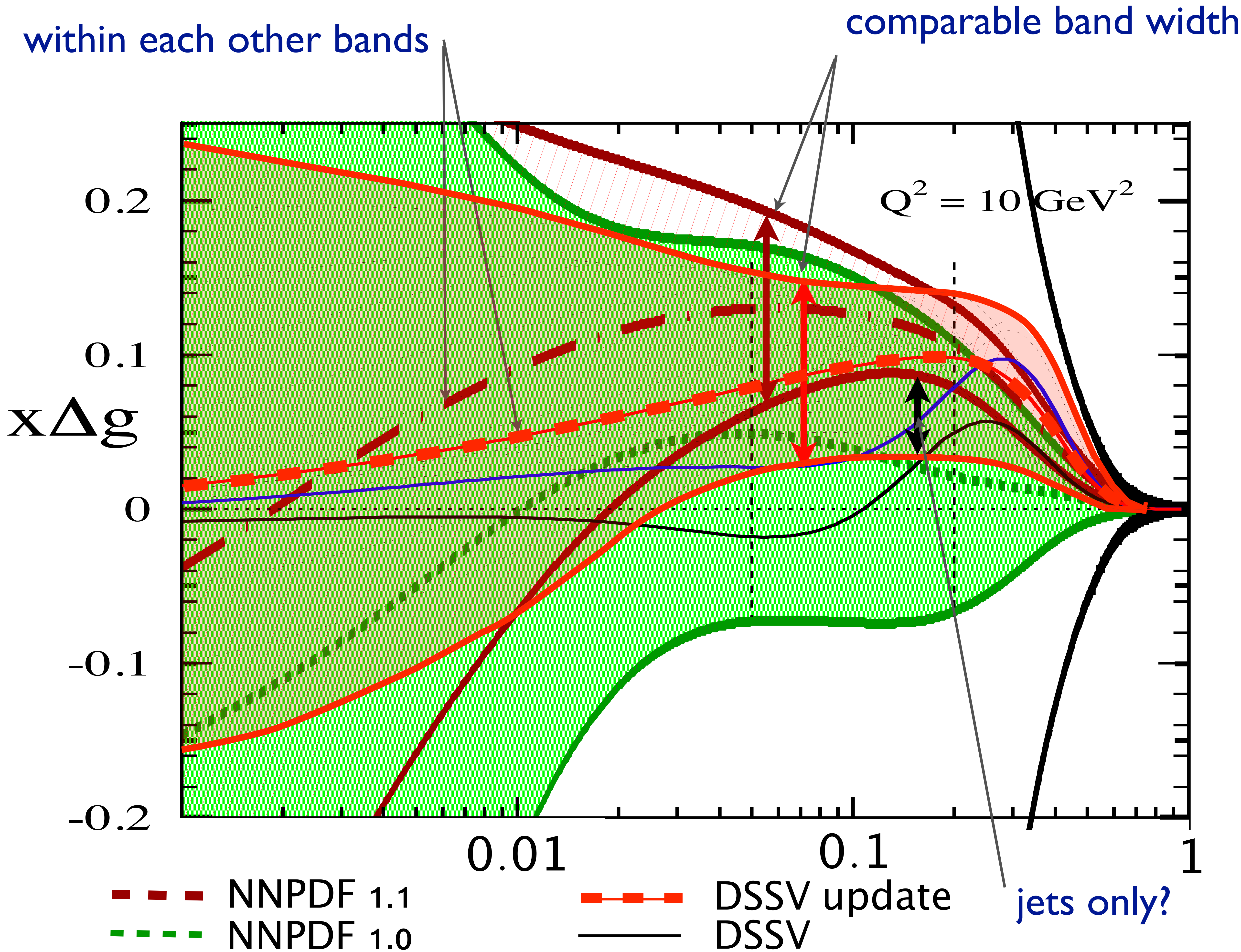
include RHIC (jets and W's) and Compass open charm data by reweighting

build and ensemble of PDFs and prune by comparison with new data

Problem: NNPDF1.0 produce only ensembles for $(\Delta q + \Delta\overline{q})$

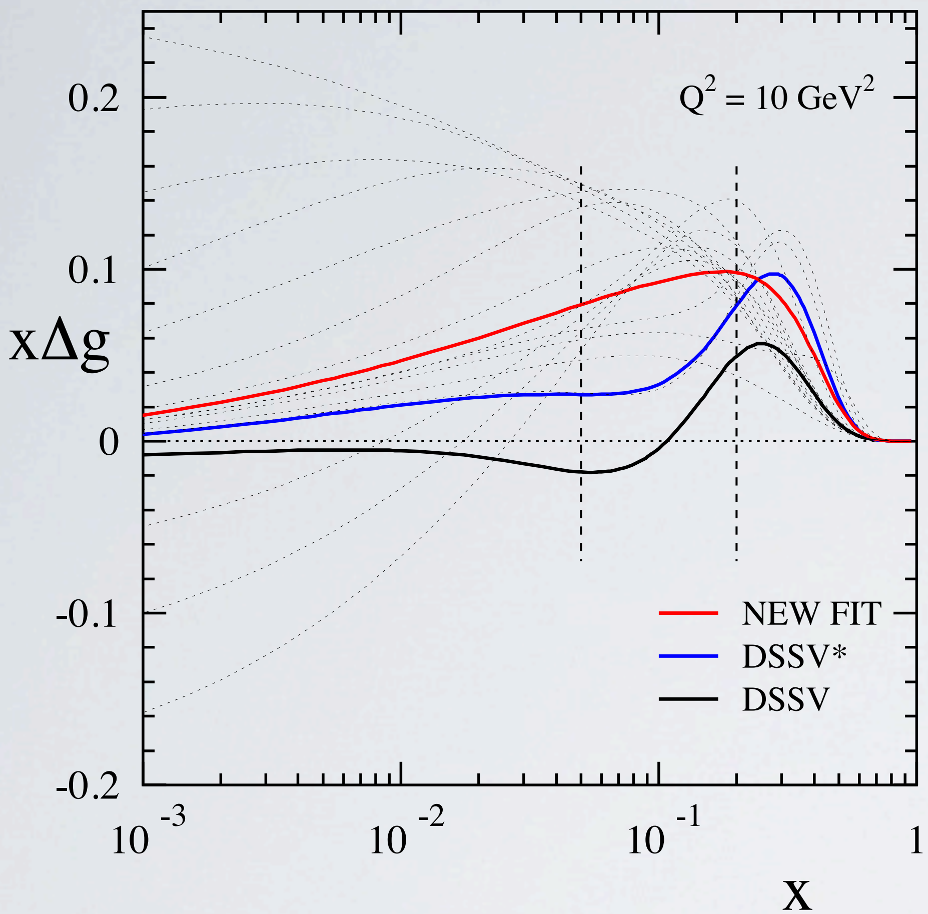
Solution: borrow DSSV $\Delta\overline{q}$ but inflating $\Delta\chi^2 = 1$ parameter errors

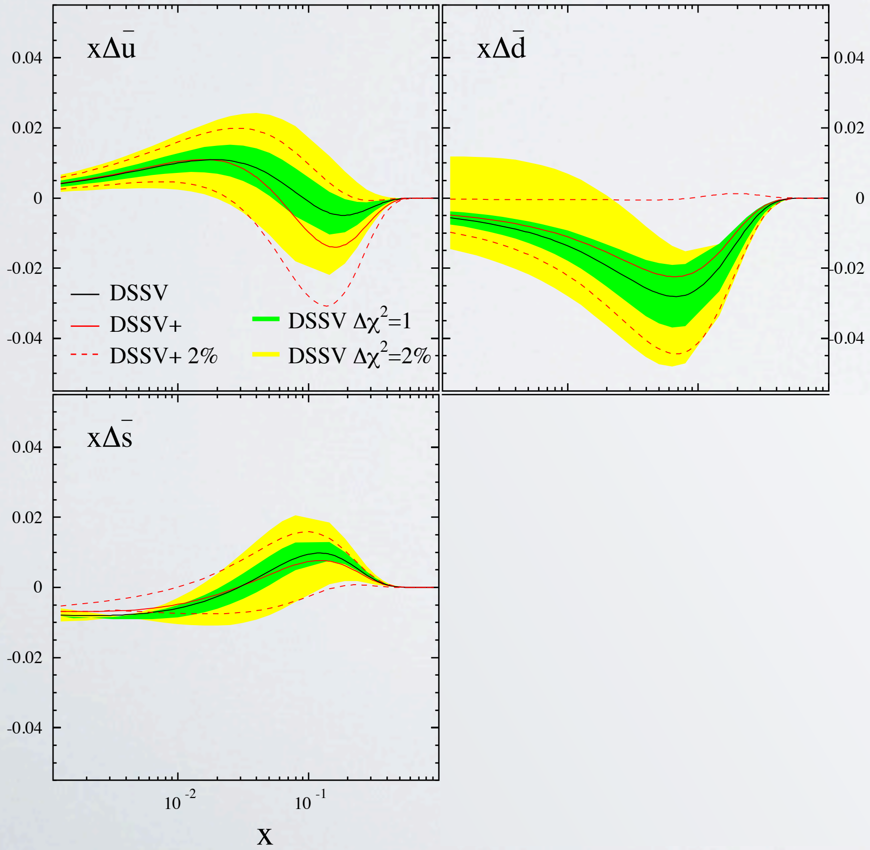
- Compass open charm has negligible impact.
- W-data produce similar effect as in DSSV++ studies
- Good agreement on the gluon polarization with DSSV gluon update



within each other bands
comparable band width
$Q^2 = 10$ GeV^2
0.2
0.1
0
-0.1
-0.2
xΔg
0.01
0.1
1
NNPDF 1.1
NNPDF 1.0
DSSV update
DSSV
jets only?

3.9 Outlook





GLUONS:

keep giving us surprises ... *nice: large!*

much better constrained by data *well done!*

progress understanding uncertainties *independent approaches*

low-x: EIC *obvious, but in long run*

forward inclusive hadrons *very welcome!*

SEA QUARKS:

much interesting than $\Delta\overline{u} = \Delta\overline{d} = \Delta\overline{s} = 0$

lots of physics involved!

flavor separation: FFs upgrade *almost done!*

Ws *framework running*

DSSV-II

coming soon